

Characterization of Operator-Reported Discrepancies in Unmanned On-Orbit Space Systems

by

David L. Ferris

Submitted to the Department of Aeronautics and Astronautics
on May 25, 2001 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Aeronautics and Astronautics

Abstract

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Statement

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The views expressed in this report are those of the author and do not reflect the official policy or position of the United States Air Force, the Department of Defense, or the United States Federal Government.

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Executive Summary

Introduction

The purpose of this research is to characterize the number and type of problems satellite operators encounter during the course of routine daily activities. Problems – regardless of cause, associated subsystem, and effect – are a source of uncertainty and cost in satellite operations. Spacecraft designers, integrators, and operators take extraordinary precautions to avoid defects once a spacecraft is on-orbit. Yet despite all the care and attention devoted to this cause, problems of all types still occur.

Unfortunately, there is a notable lack of published data concerning the day-to-day issues affecting satellite operations. What types of problems will a satellite operator encounter during a typical week, month, or year of work? How often will these problems occur? Although experienced members of an operations staff can usually provide estimates based on anecdotal evidence, there exists no precedent for making this information available to the aerospace community at large.

Several studies have documented the failure history of spacecraft components, but these studies do not capture the full scope of problems that an operator might face. On a routine daily basis, satellite operators may encounter problems completely unrelated to the spacecraft and unaffected by its performance. Lifecycle operations play an important role in a typical space system enterprise, and one that is sometimes neglected or ignored. For satellites with a long design life or a particularly complex ops concept, the operations phase may easily surpass the design and manufacturing stages in terms of time and cost. Therefore, all the problems encountered during the operations phase – including those not related to the spacecraft – should be documented, hence the motivation for this study.

The study is designed to test the following hypotheses using a verifiable, quantitative analysis:

- **First hypothesis.** Most problems encountered by an operator do not involve the spacecraft at all, but are attributed to other elements of the space system.
- **Second hypothesis.** Correlations exist between aspects of a space system design and the nature of problems experienced by the operations staff over the long term.

In the context of this paper, a discrepancy is defined as the perception by an operator that some portion of the space system has failed to operate as designed. Discrepancies can therefore include ground system malfunctions, procedural errors, and even misdiagnosis that a problem exists, in addition to actual spacecraft anomalies.

Methodology

Several government civilian and military satellite programs were contacted about contributing discrepancy data for this study. Although the names and formats of the reports varied greatly, all of the programs maintained some form of documentation for the problems they encountered. The documentation targeted for this study was the first-response problem logging or reporting performed by the on-console operators, if available. When provided in the form of hand-written logs, individual entries were first manually entered into electronic format. Hardcopy forms and incident reports were scanned using optical character recognition (OCR) software and reviewed for accuracy. Source data provided in the form of proprietary or mission-specific electronic databases were first exported to tab-delimited text files. In each of the three cases, the result was a generic text file containing all the original source data, which could be manipulated by a variety of software tools.

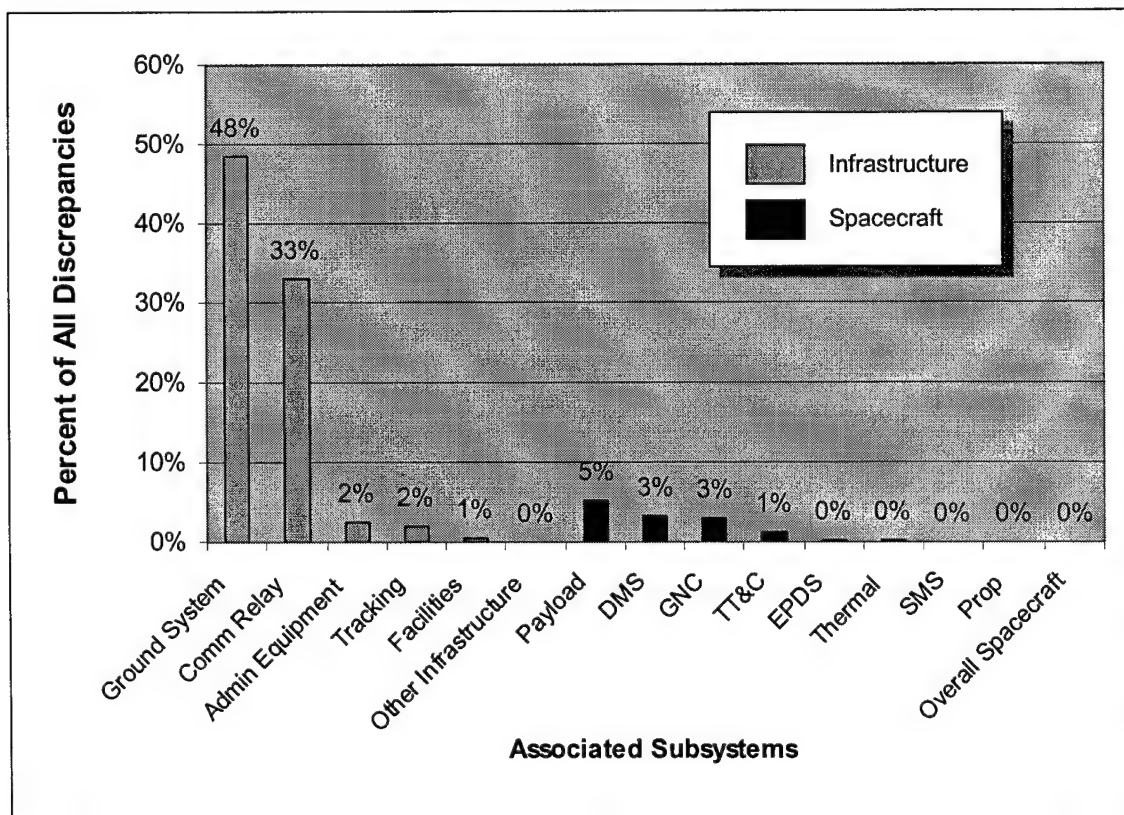
All of the source data sets used a unique format in terms of structure, data requested, field names, etc. In order merge the data into one uniform database, several modifications were made to each set. To begin with, a standard data format was defined using a core set of information common to a large majority of the source sets. Unnecessary or extraneous data fields were removed from the source data sets, and the pseudonym for the contributing organization was added to every entry in the file.

The next data preparation step was accomplished to address concerns about the release of proprietary data. References to spacecraft names, payload instruments, personnel teams, unique facilities, or specific equipment configurations were replaced with generic descriptive terms. At this point in the process, the discrepancy reports were normalized on the basis of each spacecraft. This was accomplished by dividing the number of discrepancies associated with each subsystem or cause for a given spacecraft by the sum total of the spacecraft's discrepancies. The resulting data observations for the spacecraft were a set of percentages, one for each subsystem or cause, which described the distribution of problems among the various categories.

Results

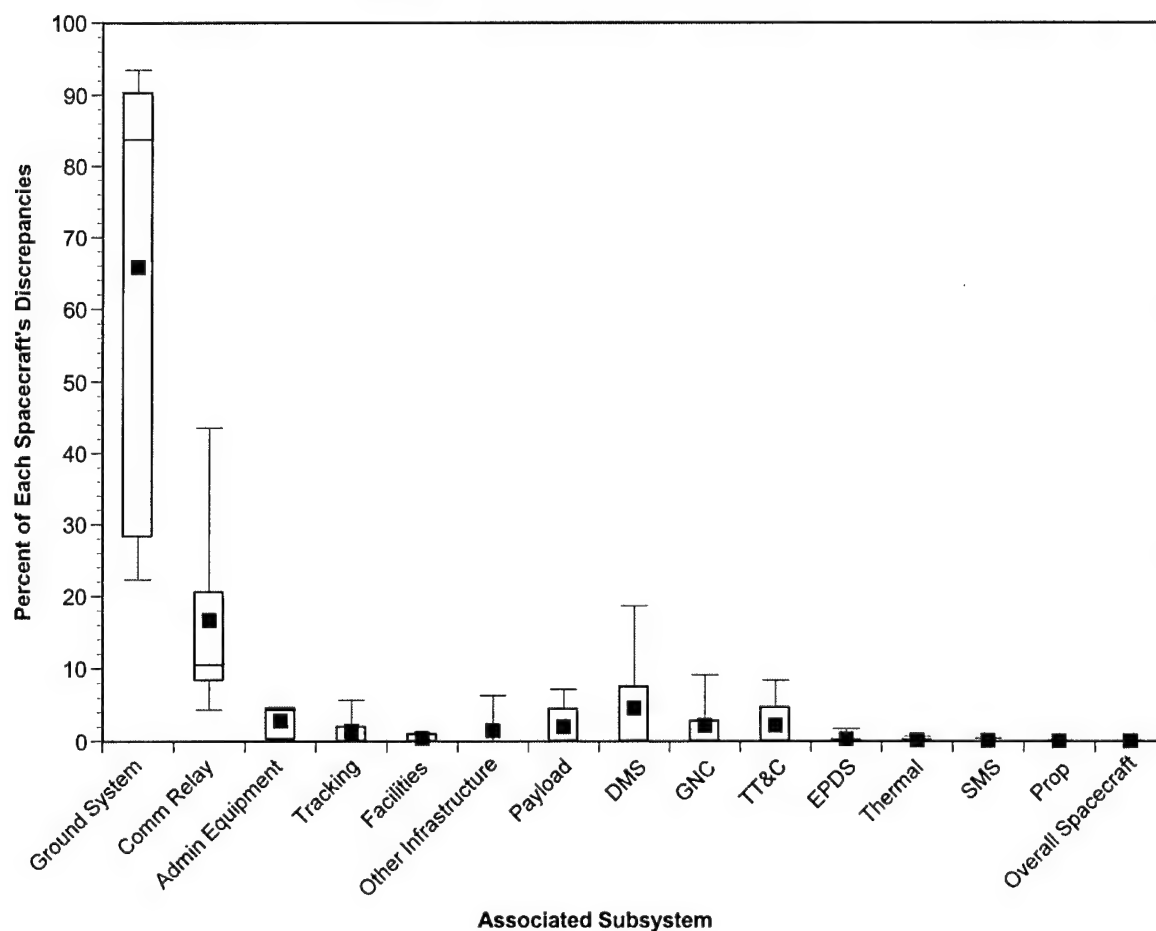
Figure 1 shows the percentage of all reported discrepancies that belong to each subsystem category.

Figure 1 – Percentage of All Discrepancies Reported vs. Associated Subsystem



The diagram indicates that the two subsystems most frequently associated with discrepancies were ground systems and communications relays. The result of the normalization process is a set of percentages representing the fraction of discrepancies for each spacecraft that are associated with each subsystem category. The percentages can be analyzed to determine whether or not a particular subsystem is consistently identified as a problem across multiple spacecraft programs. Figure 2 gives a more accurate presentation of the fact that ground systems, in particular, and to some extent communications relays are consistently attributed to discrepancies across several different spacecraft programs.

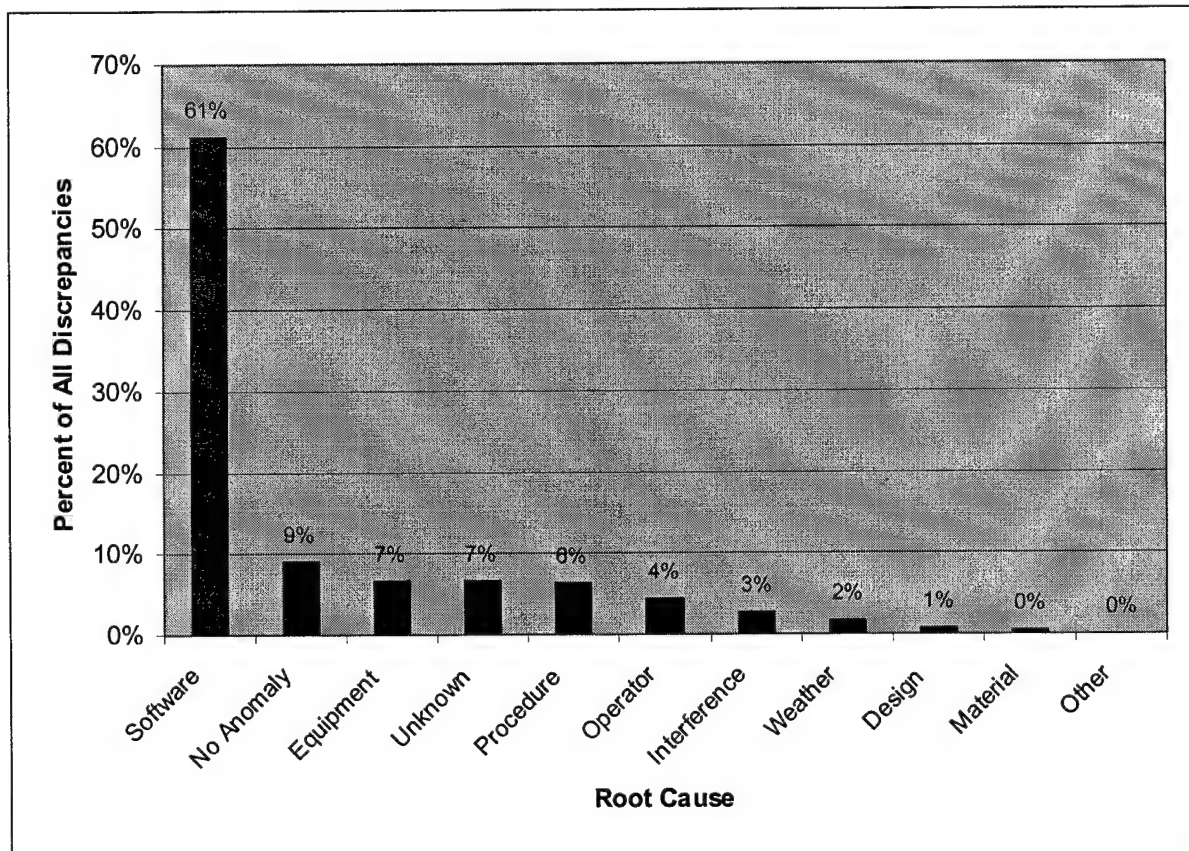
Figure 2 – Box Plot of Subsystem Statistics



Most of the discrepancy data sets contributed for this study contained root cause information in each report. Those that did not were excluded from this portion of the analysis. In a

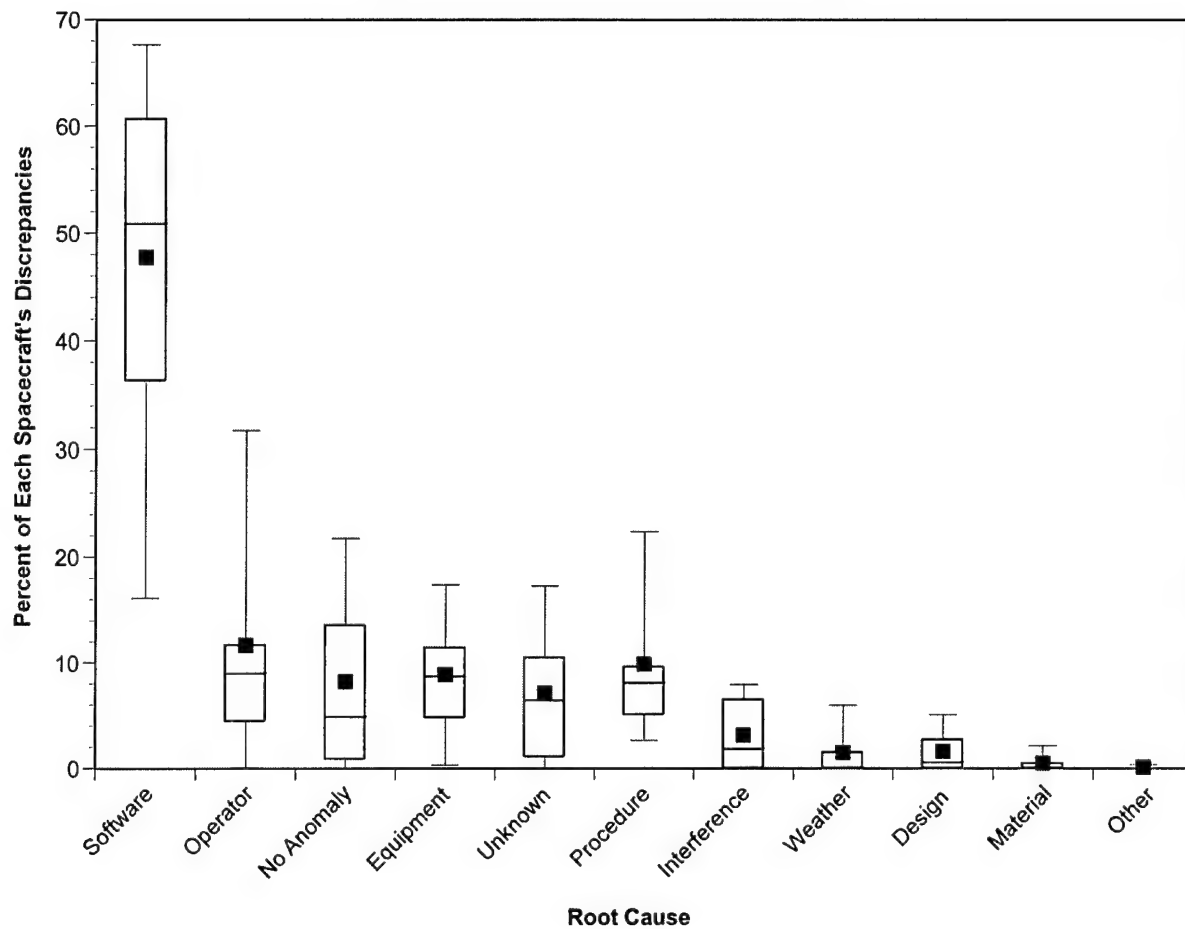
similar fashion as the subsystem category, the first step is to report the number of discrepancies belonging to each subsystem category. This is accomplished with the category relative frequency diagram shown in Figure 3. The diagram indicates that software problems are the most frequent cause of discrepancies, occurring in 61% of the reported cases. The equipment, unknown, procedure, and no anomaly categories were comparable at approximately 7% each.

Figure 3 – Percentage of All Discrepancies Reported vs. Root Cause



The normalization process can also be applied to the root cause analysis to prevent one or two spacecraft from skewing the results. When the data is normalized on a per-spacecraft basis, the resulting statistical parameters for each root cause category are shown graphically using a box plot in Figure 4. The diagram shows that software is the only root cause category consistently reported as a frequently occurring problem among all of the spacecraft in the dataset.

Figure 4 – Box Plot of Root Cause Statistics



Conclusions

An analysis of over 9,200 discrepancy reports from 11 on-orbit spacecraft supports the first hypothesis – 87% of the discrepancies collected were attributed to some component of the operational infrastructure. The remaining 13% involved one or more components on board the spacecraft. Software was the most frequently reported cause of discrepancies, found in 61% of all discrepancies documented.

The discrepancy reports also indicated that correlations do exist between certain design elements and the types of problems experienced during operations. The following correlations were found based on the data collected:

- **Ground System vs. Mission Type.** The percentage of discrepancies per spacecraft associated with the ground system tends to change given a particular mission type for the spacecraft.
- **Comm Relay vs. Ops Team.** The percentage of discrepancies per spacecraft associated with the communications relay tends to change from one organization to another.

Thus, the data collected supports the second hypothesis, but with the caveat that a sufficiently large and diverse sample set must be obtained to verify the results. It should be noted that causality cannot be determined from the statistical correlation analysis, but must be investigated on a case-by-case basis.

The results of this study can be extended by incorporating discrepancy data from additional spacecraft, particularly commercial programs. The methodology can also be applied on databases for individual satellite programs to gain insight into the nature and frequency of problems experienced by the operations staff. Ultimately, this can help supervisors identify strengths and areas for improvement in attempt to continuously improve the service provided to the user.

Chapter 1 – Introduction

There exists a great deal of literature on the theory and application of lean principles. The purpose of this section is neither to expand upon existing theory nor to serve as an exhaustive summary of available literature. It is intended to provide only a very brief introduction to lean principles so the reader will understand the context in which this research was conducted. The book *Lean Thinking*, by James Womack and Daniel Jones, contains a much more thorough treatment of this subject and is generally considered the best source on the background and application of lean principles. Thus, this chapter simply recounts the origins of lean, the creation of the Lean Aerospace Initiative (LAI), and the underlying motivation for operational satellite discrepancy research.

Origins of Lean

The origins of current theory on lean principles can be traced back to manufacturing techniques implemented at Toyota Motor Company following World War II. In the years immediately following the war, executives at Toyota searched for ways to catch up to the manufacturing capabilities of their American counterparts. The task and responsibility fell primarily on Toyota's chief production engineer, Taiichi Ohno. After several fact-finding trips to American auto factories, Ohno eventually realized that Japan simply did not have the resources or the market base to sustain the tremendous level of mass production taking place in the United States. What he needed to find, instead, was a more efficient way to deliver the exact products his customers wanted as quickly and as cheaply as possible.¹ The various manufacturing techniques he developed, and more importantly, the process by which he developed them, collectively form the basis of the management theory now known as 'lean.'

Womack and Jones summarize Ohno's approach using five principles of lean:²

¹ Ohno, Taiichi. *Toyota Production System: Beyond Large-Scale Production*. Cambridge, MA: Productivity Press, 1988. pp. 1-3.

² Womack, James P. and Daniel T. Jones. *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. New York, NY: Simon & Schuster, 1996. pp. 15-98.

- **Value.** The first and critical step is defining what is important, and therefore has value, from the perspective of the end customer. It may be a product, a service, or a combination of the two. The definition of value should include not only what the customer wants, but also how it should be provided, when it should be provided, and at what cost.
- **The Value Stream.** Once the concept of value is defined, every activity – from the collection of raw materials to the delivery, use, and maintenance of the final product – must be examined and categorized as value-added, wasteful but necessary given current constraints, or wasteful and unnecessary. Value-added activities directly contribute to the form, fit, and function of a product or the successful performance of a service. Wasteful activities generally can be categorized as one of seven types: over-production, waiting, transportation, inventory, processing, motion, and defects. The goal is to eventually completely eliminate waste from the value stream.
- **Flow.** Once the value stream is thoroughly mapped and as much waste as possible eliminated, the remaining value-added activities must be organized to allow continuous flow. Ohno's implementation focused on single-piece flow through the assembly line, as opposed to the batch-and-queue method. He achieved this using production cells capable of accomplishing their tasks according to a predefined *takt* time. The recognition of time as a critical commodity, and the emphasis on synchronizing work in a precise fashion, is one of the distinguishing characteristics of lean. Ohno also relied on personnel who were organized along product lines or processes, rather than functions or departments.
- **Pull.** Continuous flow makes it possible for a customer to 'pull' products or services from a company, rather than a company pushing products or services onto the customer. This creates a ripple effect that reaches all the way back through the value stream to the original suppliers. The combination of continuous single-piece flow and pull is sometimes called just-in-time manufacturing, which requires an ability to

rapidly changeover from one product to another and to produce parts with a defect rate near zero.

- **Perfection.** The initial implementation of the first four principles is not enough. They must be accomplished repeatedly in an iterative fashion, always looking for ways to improve the product or service and eliminate waste. This step tends to capitalize on the knowledge and expertise of the workers actually performing the tasks on a daily basis.

Even more important than the techniques Ohno developed is the process he used to implement and perfect them. These radical manufacturing improvements did not occur overnight. In fact, it took Toyota almost thirty years to tweak and fine tune its manufacturing methods, but the result was an assembly line that, by the mid-1980s, easily led in the world in terms of efficiency, flexibility, and quality.³ Success was achieved by taking advantage of workers' knowledge and expertise – and encouraging them to suggest and test improvements in a controlled, measurable, and repeatable fashion.⁴

After losing tremendous amounts of market share and profit to the Japanese in the 1980s, American automotive companies forced themselves to learn the principles of the Toyota Production System. Ford Motor Company purchased a 24% share of Mazda and set about learning as much as possible from the company's production complex in Hiroshima.⁵ GM launched a joint venture with Toyota, called NUMMI, which was located in California. In both cases, the American companies began to catch up with their Japanese counterparts. By 1989, American-owned auto factories in North America were approaching the level of productivity found in Japanese-owned plants.

³ Womack, James P., Daniel T. Jones, and Daniel Roos. *The Machine That Changed the World: The Story of Lean Production*. New York, NY: Harper Perennial, 1991. pp. 75-103.

⁴ Spear, Steven and H. Kent Bowen. "Decoding the DNA of the Toyota Production System," *Harvard Business Review*. (Sept-Oct) Case # 99509. Cambridge, MA: Harvard Business School Publishing, 1999. pp. 97-106.

⁵ Womack, James P., Daniel T. Jones, and Daniel Roos. *The Machine That Changed the World: The Story of Lean Production*. New York, NY: Harper Perennial, 1991. pp. 237-238.

Creation of the Lean Aerospace Initiative

At about the same time American automotive companies began to realize the benefits of converting to lean production, key players in the Department of Defense and industry began to question whether or not it would be possible to apply those same lessons to the aerospace sector. The Lean Aircraft Initiative was created in 1993 as a research partnership between the U.S. Air Force, the Massachusetts Institute of Technology, defense aerospace companies, and labor unions. Its original charter was to examine how the lean principles could be applied to aircraft manufacturing, but with the addition of several other government agencies and companies by 1998, the scope of the Lean Aircraft Initiative was broadened to include spacecraft and its name changed to the Lean Aerospace Initiative (LAI).

The Lean Enterprise Model (LEM) is one of the first and most significant products developed by LAI. Introduced in June 1996, the LEM is a systematic framework for organizing and disseminating MIT research and external data source results.⁶ It contains an enterprise-level summary of lean principles and overarching practices, as well as underlying metrics that are useful for quantifying and measuring various aspects of lean performance. The LEM helps members of the aerospace community find research related to particular problem areas, and can be used as a reference tool for a lean self-assessment.

This research is sponsored by the Lean Aerospace Initiative and applies to the following areas of the LEM:⁷

- **Identify and Optimize Enterprise Flow.** In order to optimize the flow of services provided by the satellite operations community, any deviations from normal operating conditions must be identified. Discrepancies, which represent such deviations, must therefore be characterized.
- **Ensure Process Capability and Maturation.** Once the deviations from normal operating conditions have been identified, steps must be taken to eliminate them

⁶ Lean Aerospace Initiative. "Welcome to the Lean Enterprise Model." Online reference, <http://lean.mit.edu/newlem2/>, March 15, 2001.

⁷ Lean Aerospace Initiative, "The Lean Enterprise Model." Summary Chart with Enabling Practices. Cambridge, MA: Massachusetts Institute of Technology. July 1998.

wherever possible. Existing satellite operations can be improved by taking action to correct the most frequently occurring discrepancies.

- **Continuously Focus on the Customer.** To prevent the same types of problems from occurring over and over again, future satellite programs can take advantage of these lessons to incorporate corrective measures directly into the design.

Motivation for Research

Early in the 1990s, lean theory expanded from its origins as a production management method to include the concept of the lean enterprise. Companies in the process of implementing lean principles realized that in order to reap the full rewards of lean, every aspect of their business – not just the factory floor – had to be improved. It became necessary to apply lean principles to business areas as diverse as purchasing, accounting, sales, shipping, logistics, and support. This extended all the way from the roots of the supplier network through the long-term use and maintenance of the product by the customer.

The aerospace sector is no exception to this rule. For a typical space system, the entire enterprise includes an acquisition or procurement branch, the integrating organization and its subcontractors and suppliers, the launch system, the operating organization and its infrastructure, and the various users of the system or data. Lifecycle operations play an important role in the enterprise, and one that is sometimes neglected or ignored. For satellites with a long design life or a particularly complex ops concept, the operations phase may easily surpass the design and manufacturing stages in terms of time and cost. Therefore, any thorough application of lean principles to a space system must include the operations phase, hence the motivation for this study.

The purpose of this research is to characterize the number and type of problems satellite operators encounter during the course of routine daily activities. Chapter 2 provides background on the need for discrepancy research within the aerospace community. Chapter 3 highlights the hypotheses tested in this thesis and provides an overview of the research structure. Chapter 4 details the characterization of discrepancies, while Chapter 5 outlines

the statistical methods used to analyze them. The results of the analyses are presented in Chapter 6, with final discussion and conclusions in Chapter 7.

LAI researcher Annalisa Weigel laid the foundation for this paper with her study of satellite manufacturing discrepancies identified during the system integration and test phase of factory operations.⁸ The methods and analyses described in Chapter 5 are kept consistent wherever possible, to allow easy and accurate comparison of results.

⁸ Weigel, Annalisa. "Spacecraft System-Level Integration and Test Discrepancies: Characterizing Distributions and Costs." Thesis. Cambridge, MA: Massachusetts Institute of Technology, 2000.

Chapter 2 – Background on Discrepancies

Problems – regardless of cause, associated subsystem, and effect – are a tremendous source of uncertainty and cost in satellite operations. Spacecraft designers add redundant subsystems to minimize the impact of problems that will inevitably occur over the lifetime of the system. Operations concepts are designed to prevent the possibility of obvious single point failures. Operators take methodically planned precautionary measures to avoid even the slightest potential for problems. Every action is taken with the knowledge that one seemingly trivial mistake can lead to the catastrophic failure of a multi-million dollar spacecraft. Yet despite all the care and attention devoted to space systems, problems of all types still occur.

Unfortunately, there is a notable lack of published data concerning the day-to-day issues affecting satellite operations. What types of problems will a satellite operator encounter during a typical week, month, or year of work? How often will these problems occur? Although experienced members of an operations staff can usually provide estimates based on anecdotal evidence, there exists no precedent for making this information available to the aerospace community at large. This chapter outlines several reasons for the lack of detailed discrepancy data, examines the corresponding impacts of the lack of data, and summarizes the potential applications of discrepancy data once it is made available.

Reasons for the Lack of Discrepancy Data

There are several reasons why satellite operations organizations do not publish discrepancy data. Although the specific reasons vary from one organization to another, and from one individual to another, they are generally comprised of some combination of the reasons outlined below:

- **Confidentiality.** Many companies fear that releasing discrepancy data reveals proprietary information about the way they conduct operations and the tools they use to do the job. Some feel that revealing this information would even cause a loss of

competitive advantage. This is in contrast to the practice of releasing status and anomaly information about the spacecraft itself, which users have a legitimate right to know. Military organizations have a similar issue in that most discrepancy data is automatically classified on the grounds it reveals too much information about the state of military readiness, or more importantly, lack thereof. The same is true of national assets, which are not represented in this study due to the security issues involved but which would undoubtedly reflect interesting trends in discrepancy data. In general, this issue can be mitigated using the data masking and normalizing techniques explained in Chapter 5.

- **Exposure of weaknesses.** There is often a general uneasiness, if not fear, amongst operators about releasing discrepancy data. It exposes intimate details about the nature of an operations facility that most people would prefer remain private. Some managers and supervisors may feel that discrepancies reflect poorly on their ability to run an operations facility, while rank-and-file operators may feel discrepancies indicate a lack of skill. Unfortunately, this hesitation is a result of human nature and is difficult to overcome. One solution is to reassure operators of the non-attribution method of data collection, masking, and reporting by an impartial third party, like LAI.
- **Additional work/cost.** Publishing data – discrepancy or otherwise – does in fact require an additional measure of labor on the part of the operations staff. In many cases, cost and staffing constraints may be so tight that the organization cannot afford the additional work. This problem can be overcome if an externally funded third party is available to perform the analysis at no additional cost and minimal effort on the part of the operations staff. This study was designed to minimize the impact of participation to approximately 10 labor-hours per organization, which typically included a background briefing, the preparation and submission of data, a follow-up interview, and a post-study debriefing.

- **Lack of perceived value.** The benefits to an operations organization of publishing its discrepancy data are not immediately apparent. Since so few organizations currently publish, or even analyze, their discrepancy data, it is easy to question the utility of such a practice. One of the goals of this study is to make the case for discrepancy data research by presenting the type of useful information gleaned from a preliminary analysis. The applications of discrepancy data research are explored more fully later in this chapter, and results of the analysis are presented in Chapter 6.
- **Lack of precedent.** When a particular practice is not commonplace within the aerospace community, as is the case with discrepancy data analysis, it typically takes a determined effort to overcome institutional inertia. The effort involved in changing the course of inertia and adopting a new practice may be too great even for proponents of the practice. At the very least, this paper can serve as one reference that discrepancy data analysis is indeed possible, and that even a rudimentary analysis can reveal meaningful insights into the conduct of satellite operations.

The methods used for this study were designed, in part, to address the concerns highlighted above. Sponsorship by the Lean Aerospace Initiative was crucial for maintaining an unbiased, impartial third-party perspective when dealing with several different organizations, some of which are in direct competition with each other.

Impacts of the Lack of Discrepancy Data

Since there is no basis for comparison, the impacts of the lack of detailed discrepancy data cannot be assessed in a quantitative fashion. However, this section will point out areas in which existing problems within the operations community can be addressed in part using a thorough analysis of discrepancy data.

Recent government acquisition reform efforts advocate, among other things, an increased awareness of system operability. Emphasis is placed on acquiring systems that are designed to improve operability. But what exactly constitutes ‘operability’ for a space system?

According to the U.S. Air Force's 2025 Final Report, the definition is "the ability to mount and sustain aerospace operations regardless of the nature of threat, level of conflict, environmental conditions, and/or geographic location."⁹ But more precise definitions of operability for a given space system can vary depending on its mission and the individual operators involved.

Since there is no universal definition for operability, another approach is to examine what operability is not. Space systems that are prone to problems are less 'operable' than space systems that are consistently trouble-free. Thus, one way to at least partially improve operability for a given space system is to find ways to prevent problems from occurring. With a lack of operational discrepancy data, however, design engineers revert back to what they know – how to prevent problems onboard the spacecraft – when in fact, they might be overlooking several larger sources of problems in the process. An analysis of discrepancy data from similar space systems would identify the largest potential sources of problems for a new space system.

There are a few examples of satellite programs that use a subset of operational discrepancy data to make improvements to future spacecraft, including the Air Force's Global Positioning System and Defense Support Program constellations, as well as NASA's TDRSS constellation. This practice results in slight modifications to each spacecraft leaving the factory, and is helpful for improving the overall quality of the product. One glaring similarity is that all three programs are large, multi-year government contracts, which makes it relatively easy for the contractor to close the design-build-operate feedback loop within the company. However, companies that build small lots of spacecraft (i.e. one) do not have the same luxury and would require historical discrepancy data from other similar programs in order to have the same effect.

⁹ Mayes, M. Scott, Felix A. Zambetti III, Stephen G. Harris, Linda K. Fronczak, and Samuel J. McCraw. "Aerospace Sanctuary in 2025: Shrinking the Bull's-Eye." 2025. Final Report, vol. 2, ch. 8. Maxwell AFB: Air University, 1996. p. 2.

Applications for Discrepancy Data

There are several different uses for discrepancy data, depending on the role of the individual performing the analysis. This section summarizes how various groups can use discrepancy data to enhance the quality of their work.

- **System architect.** Trade studies and architectural decisions made early in the concept exploration phase have a tremendous impact on the final implementation of a system. One way to avoid overlooking acceptable solutions is to create an array of models that allow an automated search of large architectural trade spaces. The Space Systems, Policy, and Architecture Research Consortium (SSPARC) methodology is an example of this approach. In order to yield meaningful results, however, the models used for the analysis must contain accurate relationships between the design inputs and the predicted performance of the resulting architecture. Although these relationships are generally well understood for the performance of spacecraft hardware, the effect design decisions have on the performance of lifecycle operations is often overlooked or ignored. Historical discrepancy data can help the system architect develop operations models using accurate, realistic relationships.
- **Spacecraft designer.** Engineers occasionally face choices on how to implement a particular design specification in a spacecraft. A typical trade study will include factors like power requirements, weight restrictions, thermal characteristics, etc. Current best practices also include factoring the reliability of the component into the trade study, and perhaps consulting with an operations representative to get a feel for which solution would be preferred. Discrepancy data would also allow the engineer to consider the impact of his or her decision on the operability of the spacecraft as another variable in the trade study, as proposed by Brandon Wood in “Development of an Operability Metric for Analysis of Conceptual Space Systems.”¹⁰
- **Operations manager.** Operations managers can use the methodology outlined in Chapter 5 to analyze their own organization’s discrepancy data. The analysis will

¹⁰ Wood, Brandon and Joyce Warmkessel. “Development of an Operability Metric for Analysis of Conceptual Space Systems.” Cambridge, MA: Massachusetts Institute of Technology, 2001.

help identify recurring problems as areas for improvement. When compared with discrepancy data from other organizations, managers can benchmark their performance and determine whether better solutions to their problems are available in the community at large.

- **Program manager.** In the most general sense, discrepancy data will help program managers understand the effect of discrepancies on the lifecycle cost of the space system. In situations where they are presented with alternate implementations for a new system or proposed changes to an existing system, program managers can use cost figures and mission impact reports from existing discrepancy data to perform a thorough cost-benefit analysis and make a well-informed decision.

The most noteworthy point regarding these applications is that, in almost all cases, detailed discrepancy data already exists. Most organizations do a thorough job documenting problems as they occur. Unfortunately, the logs are typically used only for short-term problem tracking and resolution. Occasionally, they are also researched within the organization and used as a reference when similar problems occur later in the operational lifetime. Thus, the hard work of recording the data is already being accomplished – all that remains is to make use of it.

Chapter 3 – Research Overview and Hypotheses

The purpose of this research is to characterize the number and type of problems satellite operators encounter during the course of routine daily activities. This chapter surveys existing literature on similar topics, provides an overview of the research strategy, and presents the specific hypotheses addressed by the study.

Existing Literature

Past research in the area of operational problems focuses almost exclusively on hardware failures onboard the spacecraft. One of the most comprehensive analyses available to the general public is Herbert Hecht's technical report, "Reliability Prediction for Spacecraft."¹¹ Hecht's study compiled anomaly reports for over 300 satellites launched between the early 1960s and January 1984. Spacecraft anomalies were categorized according to cause and affected subsystem, and the subsequent results used to update the MIL-HDBK-217 model for predicting spacecraft reliability.

More recent anomaly analyses are performed by the Aerospace Corporation's Space Operations Support Office (SOPSO), which maintains an anomaly database with historical data for over 400 satellites. Operational failure modes are identified based on cause, equipment type, and subsystem.¹² Correlation studies are performed to determine the effect of space weather and other factors on overall spacecraft performance.

Some studies focus on spacecraft anomalies caused by specific conditions or anomalies that occur in special circumstances. One example is Tosney and Boeck's compilation of satellite anomalies caused by the Leonid meteor shower.¹³ There are also several papers that examine

¹¹ Hecht, Herbert, and Myron Hecht. "Reliability Prediction for Spacecraft." Technical report. Griffiss Air Force Base, NY: Rome Air Development Center. December 1985.

¹² The Aerospace Corporation. "SOPSO Resources." Online reference, <http://www.aero.org/sopso/resources.html>, March 15, 2001.

¹³ Tosney, W.F., and M.L. Boeck. "Integrated satellite anomaly database – Overview, community access, and plans for future environmental events." Leonid II Meteoroid Storm and Satellite Threat Conference, Manhattan Beach, CA, May 11-13, 1999, Proceedings. Los Angeles, CA: Aerospace Corporation, 1999.

various hardware anomalies caused by the radiation environment.¹⁴ The effects of many different types of space-related phenomena have been studied in detail and documented.

Such studies are valuable for calculating hardware failure rates, reliability specifications, and model calibration constants, but do not capture the full scope of problems that an operator might face. On a routine day-to-day basis, satellite operators may encounter problems completely unrelated to the spacecraft and unaffected by its performance. This fact prompted the first hypothesis of this study, described later in this chapter.

Hypotheses

Although the discrepancy data collected for this study can help individual organizations answer several types of questions particular to their unique environment, the scope of the study is intended to address more broadly applicable issues. It examines and tests the following statements:

- **First hypothesis.** Most problems encountered by an operator do not involve the spacecraft at all, but are attributed to other elements of the space system.
- **Second hypothesis.** Correlations exist between aspects of a space system design and the nature of problems experienced by the operations staff over the long term.

The first hypothesis investigates the notion that the infrastructure of a space system is generally more problem-prone than the spacecraft itself. Although there is a measure of agreement within the operational community that this assertion is true,¹⁵ it has not yet been proved or disproved in an analytical fashion. For the purposes of this study, the infrastructure of a space system consists of the following:

- **Ground system.** Includes both the hardware and software deployed to decrypt, decommutate, calibrate, display, and archive satellite telemetry and mission data.

¹⁴ Lauriente, M., A.L. Vampola, R. Koga, and R. Hosken. "Analysis of spacecraft anomalies due to the radiation environment." *Journal of Spacecraft and Rockets*, vol. 36, no. 6, Nov-Dec 1999, pp. 902-906.

¹⁵ Based on interviews with satellite operators from several different organizations.

Also includes equipment used to format, validate, and encrypt commands. Most elements of the human-computer interface fall into this category.

- **Communications relay.** Includes routers, switches, patch panels, landlines, microwave transmissions, satellite relays, ground station antennas and RF equipment, and communication satellites. The exact equipment included in this category varies greatly depending on the ops concept used for a particular mission, and may be anything from a single, dedicated satellite dish to a shared, global communications network.
- **Tracking equipment.** Includes hardware and software necessary to perform RF and/or optical pointing and ranging techniques. This equipment is often collocated with elements of the communications relay, but may also be provided by an external source as a service to the program.
- **Facilities.** Includes the physical structures in which equipment and personnel are housed, access controls to said structures, utilities such as water and electricity, and heating and cooling systems.
- **Administrative equipment.** Includes all other hardware and software used to support operations either directly or indirectly, like telephones, fax machines, offline computers, printers, etc.

The second hypothesis investigates the possibility that certain design choices typically made early in the product development phase correlate with specific, predictable types of problems experienced in the operational phase. Care is taken here not to imply that such correlations indicate cause-and-effect relationships. Since the true root cause in each relationship may vary from one satellite design to another, root cause analyses should be performed on a case-by-case basis and are therefore outside the scope of this research. However, the presence of a correlation definitely indicates an area that merits further investigation. The specific design elements examined as part of this study are:

- **Mission type**
- **Communications relay scheme**
- **Spacecraft altitude**
- **Orbit characteristics**
- **Attitude control scheme**
- **Complexity**
- **Multiple spacecraft/constellation**

Details concerning each design element are included in Chapter 4. The design elements were selected on the basis of availability of pertinent data and the likelihood of a correlation.

Additional design elements that failed to meet both of the criteria, but are still valid for future study, include:

- **Available reserve on-board memory capacity at launch**
- **Telemetry/command format used**
- **Type of ground system software used**
- **Number of telemetry measurands sampled**
- **Communications subsystem link margin at launch**
- **Thermal subsystem design margin at launch**
- **Solar array/battery type**

Research Structure

This research stems from key questions facing the Test & Space Operations focus team within LAI:

- What kinds of problems are operators having?
- Can we do anything to fix existing problems, predict new ones, and ultimately prevent them from occurring?

Recognizing that anomalous conditions increase the variability and cost of performing satellite operations, it is desirable to avoid or prevent problems wherever possible. It is not

coincidental that these two questions directly relate to the lean principles of eliminating waste and pursuing perfection. The rest of this section provides an overview of how these two questions were translated into the analysis method described in Chapter 5.

Although it may be possible to address the first key question within a strictly theoretical framework, such an approach can easily become divorced from reality. Therefore, the best way to answer the question is to characterize the types of actual problems satellite operators experience over the lifetime of each vehicle they control. Normally, an applied approach like this would require researchers to implement data collection procedures at each facility targeted for study.

Fortunately, it is and has been fairly common in the satellite operations community to log problems, or symptoms of problems, when they occur. Thus, the most labor-intensive, long-term work has already been performed. What remained was to collect the factual data from a fairly large sample of organizations. This proved to be more difficult than expected, due to the reasons discussed in Chapter 2.

Since there is no industry standard format for logging discrepancy data, it was also necessary to develop procedures to merge each log on a case-by-case basis. For some databases, it was merely a matter of selecting appropriate fields for inclusion. For others, the procedure involved manually reviewing each discrepancy in order to properly categorize it. Once the submitted data was compiled into one data set, a thorough analysis could be performed using well-established statistical techniques.

The second key question is more difficult to attack. Although the main thrust of the question is to fix existing problems and eventually prevent new problems from occurring, such an ambitious goal is beyond the scope of this research. The focus will be instead to find an additional tool for predicting problems before they occur. In a risk-adverse community such as the aerospace sector, this goal alone would be helpful if accomplished. And once the problems are identified, managers, engineers, and operators have considerable knowledge and expertise in dealing with them.

One way to predict future problems is by investigating trends in the discrepancy reports from similar spacecraft that already on-orbit. Since a comprehensive data set of operational discrepancies was already required to address the first key question, what remained was finding relationships between the recorded problems and an unknown set of independent variables. This research had to identify one of the true independent variables and then determine its relationship to the dependent variables, the number and type of problems that occur during lifecycle operations.

The method used to accomplish this task was a simple, brute force approach. In other words, a candidate independent variable was selected, and then analyzed to determine if a relationship existed with the dependent variables. If no correlation existed, the candidate independent variable was discarded. If a correlation did exist, a ‘true’ independent variable was considered found. Since the number of possible independent variables is virtually unlimited, the pool from which candidate variables were chosen was narrowed down using three criteria:

- **Design element.** To begin with, only elements of a typical spacecraft design were considered for analysis in this study.
- **Potential for correlation.** The candidate independent variables selected for examination were those for which intuition suggested a possible relationship.
- **Availability of data.** Of the remaining variables, the ones finally studied were those for which sufficient data existed to perform the analysis.

The convergence of the three criteria is reflected in the second hypothesis, below. The approach just described does not predict a problem per se, but identifies the potential for a problem to occur. The shortcomings to this approach – namely, predicting future problems based on past performance, merging data collected using different procedures, and the existence of other untested independent variables – will be discussed in more detail in Chapter 7.

Chapter 4 – Discrepancies Defined

This paper defines a discrepancy as the perception by an operator that some portion of the space system has failed to operate as designed. Thus, discrepancies can include ground system malfunctions, procedural errors, and even misdiagnosis that a problem exists – in addition to actual spacecraft anomalies. This chapter further defines discrepancies by describing the information collected for each one, outlining their possible causes, and describing the affected subsystems.

Data Collected for Each Discrepancy

As noted previously, operators log discrepancy events each time they occur. Since there is no standardized format, the information included in each log varies from one organization to another. Procedures at one facility may call for a very detailed report of the circumstances surrounding the incident and the resulting action taken, while procedures at another facility may require only a brief description of the symptoms observed. In addition, the logs vary considerably based on the style of the operator actually recording the data.

For the purpose of this study, however, a minimum standard discrepancy report had to be defined. Due to level of variation in the source data, only the most basic information was included in the format to avoid excluding substantial blocks of source data. The fields chosen for the discrepancy format were:

- **Organization.** The pseudonym used to represent the organization responsible for operating the spacecraft.
- **Satellite associated with discrepancy.** The pseudonym used to represent the specific satellite associated with the discrepancy. In some cases, discrepancies were not associated with any one particular spacecraft and were noted as such.
- **Date of discrepancy.** The date on which the discrepancy occurred.

- **Description of discrepancy.** A brief summary of the discrepancy. Any identifying information was replaced with a generic designator.
- **Affected subsystem.** The subsystem within the space system most closely associated with the discrepancy. The categorization system used for the field is described later in this chapter.
- **Root cause (if identified).** When available in the source data, the root cause of the discrepancy was included in the report. Discrepancies for which the root cause was not identified were not included in any analysis requiring the information. The categorization system used for the field is described later in this chapter.

In addition to the information collected for each discrepancy, several data points pertaining to design elements were collected for each spacecraft. The data points were then linked to all the discrepancies associated with the corresponding spacecraft. The design elements consisted of the following:

- **Mission type.** The category that best describes the mission of the spacecraft. Choices include remote sensing, communications, research & development, weather, observatory, and other.
- **Communications relay scheme.** Examines the primary method used to relay spacecraft commands, state of health telemetry, and payload data from the mission control center to the spacecraft and back. Choices include one dedicated ground station; multiple dedicated ground stations; shared ground station network, specifically the NASA Deep Space Network, the Air Force Satellite Control Network, and the NASA GN; other shared ground station network; and shared space relay network, specifically NASA TDRSS.
- **Spacecraft altitude.** Examines the altitude region in which the satellite operates. Choices include low, for orbits located entirely in the region below 1,000 km

altitude¹⁶; medium, for orbits located entirely in the region 1,000 – 25,000 km altitude; high, for orbits located entirely in the region above 25,000 km altitude; and multiple, for elliptical orbits passing through two or more of the previous regions.¹⁷

- **Orbit characteristics.** Examines a subset of special cases for the type of orbit used. Choices include sun-synchronous; polar, for polar and near-polar orbits with an inclination in the range 83° – 97° (other than sun-synchronous); geosynchronous; geosynchronous transfer orbit; and South Atlantic Anomaly, for orbits which pass through the SAA. Note that these categories do not include all possible orbit configurations. These special cases were singled out due to the potential for specific types of discrepancies associated with each one.
- **Attitude control scheme.** Examines the type of attitude control incorporated in the spacecraft design. Choices include gravity gradient stabilized, spin stabilized, three-axis stabilized, and free tumble.
- **Complexity.** This general qualitative description is a composite of several design elements, including number of telemetry measurands sampled, number of nodes in the communications relay, number of payloads on board the spacecraft, acceptable tolerances for operating constraints (e.g. pointing accuracy, stationkeeping window, and thermal limits), complexity of onboard software, and time criticality for performing operational activities. Choices include low, medium, and high.
- **Multiple spacecraft/constellation.** Examines whether the satellite is part of a production line of multiple similar spacecraft, and if so, whether the spacecraft is the first off the line. Choices include no, first, and yes.

¹⁶ Gorney, D.J., J.B. Blake, H.C. Koons, M. Schulz, A.L. Vampola, R.L. Walterscheid, and J.R. Wertz. "The Space Environment and Survivability." *Space Mission Analysis and Design*. 2nd ed. Torrance, CA: Microcosm, 1993. pp. 199-201.

¹⁷ The given regions are selected to correspond with the approximate floor altitude of the inner and outer zones of the Van Allen radiation belts, which provide convenient demarcation points.

Lastly, each organization included in the data set was categorized as one of the following types: civil, military, commercial, academic, and other. The data for organization type was then linked to all the discrepancies reported by the corresponding organization. The categorization system described above provided a concise way to group similar types of discrepancies during the analysis process.

Causes of Discrepancies

Discrepancies can be caused by a number of factors. When a root cause was identified in the source data, one of the following categories was assigned to the corresponding discrepancy:¹⁸

- **Employee/operator.** Discrepancies caused by a person incorrectly executing a procedure, sending an unintended command, altering mission critical equipment, etc.
- **Design.** Discrepancies caused by problems in the design of the spacecraft or ground system. Applied in cases where the component in question is verified as meeting design specifications but still causing an undesirable condition.
- **Procedure.** Discrepancies caused when a procedure is executed as written and later identified as incorrectly planned. Weigel's paper originally included this category as part of Design, but is separated here due to the procedural nature of operations.
- **Material.** Discrepancies caused by defective equipment, parts, material, etc. on the spacecraft, as can best be determined through analysis. Also includes equipment or components on the spacecraft that have failed to meet design specifications.
- **Equipment.** Discrepancies caused by defective equipment, communications lines, computers, cables, etc. not on the spacecraft. This category focuses primarily on instances of verified hardware failure.

¹⁸ Weigel, A.L. "Spacecraft System-Level Integration and Test Discrepancies: Characterizing Distributions and Costs." Cambridge, MA: Massachusetts Institute of Technology, 2000. pp. 25-26.

- **Software.** Discrepancies caused by software, either on the spacecraft or on the ground equipment. Includes problems caused by hung processes, or instances where a computer reboot is required to restore functionality.
- **Interference.** Discrepancies caused by radio frequency interference with other spacecraft, communications relay line quality degradation or noise, or scheduling conflicts with other spacecraft.
- **Weather.** Discrepancies caused by external environmental factors, including storms that affect ground stations, single event upsets on the spacecraft caused by radiation, problems associated with suspected debris or meteor hits, etc.
- **No Anomaly.** Discrepancies written up in error, or determined later to not be anomalies, etc. This includes discrepancy reports written up for informational purposes, or to request adjustments to telemetry limit values.
- **Unknown.** Discrepancies whose cause is unknown or unable to be determined.
- **Other.** Discrepancies that do not fall into the previous eight categories.

In general, discrepancies have one root cause. In the occasional case that a discrepancy had two or more root causes, it counted against the multiple corresponding categories above.

Affected Subsystems

Discrepancies are usually associated with one particular subsystem or another. The following categories were used for subsystems *onboard the spacecraft*:

- **Electrical Power and Distribution System (EPDS).** EPDS's primary function includes the generation, regulation, storage, and distribution of electrical/electronic power throughout the vehicle. Other names: Electrical Power Subsystem (EPS),

Power Subsystem, Power.¹⁹ Includes, but is not limited to, solar arrays, batteries, switching circuitry, and power supply regulators.

- **Guidance, Navigation and Control (GNC).** The GNC subsystem's primary function provides determination of orbit and attitude, plus pointing of spacecraft and appendages. Other names: Attitude Control Subsystem (ACS), Attitude Determination and Control Subsystem (ADCS).²⁰ Includes, but is not limited to, sun sensors, horizon sensors, gyros, magnetic torquers, GPS receiving equipment, and attitude determination and control processors.
- **Payload.** The payload subsystem's primary function provides mission specific capabilities to the space vehicle's functionality. This is the single most significant driver of spacecraft design. Payloads have various capabilities such as communication, navigation, science, imaging, radar, and others.²¹
- **Propulsion (Prop).** The propulsion subsystem's primary function provides thrust to adjust orbit and attitude, and to manage angular momentum. Other names: Reaction Control Subsystem (RCS).²² Includes, but is not limited to, propellant tanks, thrusters, plumbing, and valves.
- **Structures and Mechanisms Subsystem (SMS).** SMS's primary function provides support structure, booster adaptation, and moving parts. Other names: Structural, Structures and Mechanisms.²³ Includes, but is not limited to, trusses, panels, hinges, and pyrotechnics.

¹⁹ Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

²⁰ Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

²¹ Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

²² Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

²³ Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

- **Data Management Subsystem (DMS).** The Data Management Subsystem's primary function distributes commands and accumulates, stores, and formats data from the spacecraft and payload. Other names: Command and Data Handling (C&DH), Spacecraft Computer System, Spacecraft Processor.²⁴ Includes, but is not limited to, telemetry sampling circuitry, solid state memory, data recorders, and central processors.
- **Telemetry, Tracking, and Command (TT&C).** The TT&C subsystem's primary function provides communication with ground and other spacecraft. Uplink data consists of commands and ranging tones while downlink data consists of status telemetry, ranging tones, and may include payload data. Other names: Communications Subsystem. Includes, but is not limited to, receivers, transmitters, and wide-angle antennas.²⁵
- **Thermal.** The Thermal Control Subsystem's primary function maintains spacecraft equipment within allowed temperature range. Other names: TCS, Environmental Control Subsystem (ECS). Includes, but is not limited to, radiators, louvers, heat sinks, heaters, and cryogenic cooling systems.²⁶
- **Wiring and Cabling (Harness).** Wiring and cabling that is not considered part of a particular subsystem called out above.²⁷
- **Other Spacecraft.** Discrepancies that are traceable down to the subsystem level, but the subsystem does not fall into one of the above categories.²⁸

²⁴ Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

²⁵ Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

²⁶ Quintero, A.H. "Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template." Los Angeles, CA: Aerospace Corporation, 1996. p. 26.

²⁷ Weigel, A.L. "Spacecraft System-Level Integration and Test Discrepancies: Characterizing Distributions and Costs." Cambridge, MA: Massachusetts Institute of Technology, 2000. p. 25.

²⁸ Weigel, A.L. "Spacecraft System-Level Integration and Test Discrepancies: Characterizing Distributions and Costs." Cambridge, MA: Massachusetts Institute of Technology, 2000. p. 25.

- **Spacecraft.** Discrepancies that cannot be traced down to a particular subsystem called out above fall into this category.²⁹

The following categories were used for subsystems *other than those on the spacecraft*:

- **Ground System.** Includes both the hardware and software deployed to decrypt, decommutate, calibrate, display, and archive satellite telemetry and mission data. Also includes hardware and software used to format, validate, and encrypt commands. Most elements of the human-computer interface fall into this category. This equipment is typically all located in the mission operations control center.
- **Communications Relay.** Includes routers, switches, patch panels, landlines, microwave transmissions, satellite relays, ground station antennas and RF equipment, and communication satellites. The exact equipment included in this category varies greatly depending on the ops concept used for a particular mission, and may be anything from a single, dedicated satellite dish to a shared, global communications network.
- **Tracking Equipment.** Includes hardware and software necessary to perform RF and/or optical pointing and ranging techniques. This equipment is often collocated with elements of the communications relay, but may also be provided by an external source as a service to the program.
- **Facilities.** Includes the physical structures in which equipment and personnel are housed, access controls to said structures, utilities such as water and electricity, and heating and cooling systems.
- **Administrative Equipment.** Includes all other hardware and software used to support operations either directly or indirectly, like telephones, fax machines, offline computers, printers, etc.

²⁹ Weigel, A.L. "Spacecraft System-Level Integration and Test Discrepancies: Characterizing Distributions and Costs." Cambridge, MA: Massachusetts Institute of Technology, 2000. p. 25.

- **Other Infrastructure.** Includes subsystems not belonging to any of the five categories listed above.

In general, discrepancies are associated with one particular subsystem. In the occasional case that a discrepancy affected two or more subsystems, it counted against the multiple corresponding categories above.

Chapter 5 – Methods and Procedures

This chapter provides a detailed explanation of the procedure used to collect, convert, and merge source discrepancy data from each contributing organization. Background information on the statistical methods used to analyze the compiled data set is presented, along with a description of the steps involved in the actual analysis.

Data Collection Procedure

The first step in collecting source discrepancy data was to contact a member of the operations staff from each program of interest, either directly or by referral. Generally, the individual authorized to release source data – and therefore the best to contact directly – was the Mission Director, Mission Operations Manager, or equivalent. A background briefing that explained the study and its objectives was provided to each participating organization. After further discussions and occasionally legal department review, the source data was released for research purposes.

When provided in the form of hand-written logs, individual entries were first manually entered into electronic format. Hardcopy forms and incident reports were scanned using optical character recognition (OCR) software and reviewed for accuracy. Source data provided in the form of proprietary or mission-specific electronic databases were first exported to tab-delimited text files. In each of the three cases, the result was a generic text file containing all the original source data, which could be manipulated by a variety of software tools.

All of the source data sets used a unique format in terms of structure, data requested, field names, etc. In order merge the data into one uniform database, several modifications were made to each set. To begin with, a standard data format was defined using a core set of information common to a large majority of the source sets:

- **Organization.** The pseudonym used to represent the organization responsible for operating the spacecraft.
- **Satellite associated with discrepancy.** The pseudonym used to represent the specific satellite associated with the discrepancy. In some cases, discrepancies were not associated with any one particular spacecraft and were noted as such.
- **Date of discrepancy.** The date on which the discrepancy occurred.
- **Title.** A short identifier for the discrepancy entry, usually a phrase or single sentence.
- **Description.** A brief summary of the discrepancy. Any identifying information was replaced with a generic designator.
- **Affected subsystem.** The subsystem within the space system most closely associated with the discrepancy. The categorization system used for the field is described in Chapter 4.
- **Root cause (if identified).** When available in the source data, the root cause of the discrepancy was included in the report. Discrepancies for which the root cause was not identified comprised 7% of all reports collected, and were not included in any analysis requiring that information.

Unnecessary or extraneous data fields were removed from the source data sets, and the pseudonym for the contributing organization was added to every entry in the file. In a few cases, the source data set did not explicitly break out one of the fields listed above (e.g. affected subsystem), and the data for that field had to be manually extracted from one of the other fields, usually the description. Figure 5 shows the database tool used to review and import each discrepancy report. Following these modifications, the data sets uniformly consisted of the information listed above.

Figure 5 – Discrepancy Report Import Tool

Discrepancy Import Screen

Original Discrepancy Data

Entity: 106
 Organization: B
 Spacecraft: 2
 Identifier: 106
 Date: 12/31/1996
 Title: GMT inability to recognize leap year
 Description: At the change of the day, the GMT went from 1996 DAY 365 to 1997 DAY 001. Initially only a few areas were impacted such as no clock correlation and no delogs. At 02:54 however FEP1 and FEP2 clock lines were reinitialize somehow. The new GMT then became 70-001-00:00:00 and did not increment. At this point all operations dealing with the GMT time tag failed. This included such things as inability to open history and block files and inability to receive UPDs. It should be noted that the GMT clocks were fine and were able to change to DAY 366.
 Subsystem: FEP
 Cause: It was discovered that the problem was software related. (Organization) maintenance then suggested the idea to manually enter the right time into the (Component) time decoder card on the front end. This was done by running a cable from the time decoder card to the keyboard connected to the FEP. Before the time was inputted the reset button was pushed on the front end.
 Import: ☐

Imported Discrepancy Data

Organization: B
 Spacecraft: 2
 Date: 12/31/1996
 Title: GMT inability to recognize leap year
 Description: At the change of the day, the GMT went from 1996 DAY 365 to 1997 DAY 001. Initially only a few areas were impacted such as no clock correlation and no delogs. At 02:54 however FEP1 and FEP2 clock lines were reinitialize somehow. The new GMT then became 70-001-00:00:00 and did not increment. At this point all operations dealing with the GMT time tag failed. This included such things as inability to open history and block files and inability to receive UPDs. It should be noted that the GMT clocks were fine and were able to change to DAY 366.
 Subsystem: Ground System
 Cause: Software
 Working closely with (Organization), who was experiencing similar problems, it was determined that maybe it was a (Organization) line problem. Notified the (Organization) switch. It was determined that there are two lines feeding off the (Organization) (Component) generator. These two lines supply the GMT time for all of the operations centers. One was working correctly and one did not recognize the leap year. This was fixed and at that point both FEP1 and FEP2 could not recognize the GMT time at all and could only display 70-001-00:00:00.
 Every time the front end reset button is pushed it resets the GMT card, so if the front end needs to be rebooted (Organization) maintenance must be called again to input the correct time manually. Operations should return to normal when 1997 comes.

Copy Fields Accept Close Form

Record: 14 | 106 | of 318

The remaining data preparation steps were accomplished to address concerns about the release of proprietary data. Any occurrence in the data of a spacecraft name was replaced with the corresponding pseudonym. References to payload instruments, personnel teams, unique facilities, or specific equipment configurations were replaced with generic descriptive terms. At this point in the process, each data set was purged of identifying information and ready to be added to the discrepancy database.

Statistics Background

It is important to note that the true population of interest is the set of all discrepancies occurring for all spacecraft launched by all nations since the first satellite, Sputnik. The only

caveat is that recent discrepancy data is more relevant, and therefore of more interest, than discrepancy data from older programs. Unfortunately, it is impossible to measure the entire population, for reasons discussed in Chapter 7. Therefore, only a sample of the population was collected and measured for this study. Discrepancy data for on-orbit spacecraft were requested from several organizations in a variety of mission areas. Strictly speaking, the emphasis on spacecraft that are currently operational is not a representative sample of the entire population. It does, however, capture data that is the most relevant to other current and future programs.

Key characteristics of the sample set are used to draw conclusions about the greater population. Although this approach is well established and widely accepted, it is necessary to verify the proper application of the technique to this particular case. Since they form the foundation of the analysis conducted here, the concepts associated with basic inferential statistics are briefly reviewed next. A more thorough treatment of the subject can be found in Mendenhall and Sincich's *Statistics for Engineering and the Sciences*.³⁰

Measures of Central Tendency

Measures of central tendency are the first of four groups of numerical descriptive measures computed from a set of quantitative data. They are a collection of mathematical techniques used to help locate the center of the relative frequency distribution. Each technique has strengths and weaknesses that make it more useful and accurate in some cases, but not others. The 'best' measure of central tendency for a given data set depends both on the type of descriptive information desired and the nature of the data being evaluated. This section reviews all of the measures of central tendency used in the discrepancy analysis.

Sample Mean

The sample mean of a set of n measurements, y_1, y_2, \dots, y_n , taken from a larger population is the average of the measurements:

³⁰ Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992.

$$\bar{y} = \frac{\sum_{i=1}^n y_i}{n} \quad (1)$$

Although the mean is often the preferred measure of central tendency, it is sensitive to very large or very small observations. Consequently, the mean will shift toward the direction of skewness and may be misleading in some situations.³¹

Sample Median

The median of a set of n measurements, y_1, y_2, \dots, y_n , is the middle number when the measurements are arranged in ascending (or descending) order. In other words, it is the value of y located so that half the area under the relative frequency histogram lies to its left and half the area lies to its right. If the number of measurements in a data set is odd, the median is the measurement that falls directly in the middle when the measurements are arranged in ascending order. If the number of measurements is even, the median is defined as the average of the two middle measurements when the measurements are arranged in ascending order. The median is sometimes called a resistant measure of central tendency since it, unlike the mean, is resistant to the influence of extreme observations. For data sets that are extremely skewed, the median would better represent the center of the distribution data.³²

5% Trimmed Mean

The 5% trimmed mean represents a compromise between the two extremes of sample mean and sample median. It is computed by ordering the values within the data set from smallest to largest, trimming 5% of the values from the top and 5% of the values from the bottom of the data set, and then computing the usual sample mean as described above for the data that remain. This prevents unusual outlier and extreme values in the tails of the distribution from affecting the size of the sample mean, and makes the trimmed mean measurement more resistant than the sample mean measurement. While it still is not as resistant as the sample median measurement, the benefit of the trimmed mean measurement is that it is based on

³¹ Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. pp. 28-29.

³² Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. pp. 28-29.

more values than the sample median measurement while effectively dealing with outliers and extreme values.³³ The number of data points to be excluded from each tail of the data set is calculated by multiplying the total number of observations by 0.05 and rounding the result down to the nearest integer.

Measures of Variation

Measures of variation are the second group of numerical descriptive measures. They are a collection of mathematical techniques used to describe the spread of measurements over the entire range of values. As before, each technique has strengths and weaknesses that make it more useful and accurate in some cases, but not others. The ‘best’ measure of variation for a given data set depends both on the type of descriptive information desired and the nature of the data being evaluated. This section reviews all of the measures of variation used in the discrepancy analysis.

Sample Range

The range is equal to the difference between the largest measurement and the smallest measurement in a data set. It is possible that two different data sets could possess the same range, but differ greatly in the amount of variation in the data. Consequently, the range is a relatively insensitive measure of data variation.³⁴

Sample Variance

The sample variance of a set of n measurements, y_1, y_2, \dots, y_n , taken from a larger population is defined to be:

$$s^2 = \frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n-1} = \frac{\sum_{i=1}^n y_i^2 - \frac{\left(\sum_{i=1}^n y_i\right)^2}{n}}{n-1} \quad (2)$$

³³ Entire paragraph drawn from Wilcoxon, Rand R. *Statistics for the Social Sciences*. San Diego: Academic Press, 1996. pp. 15-16.

³⁴ Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. pp. 30-31.

The sample variance is primarily of theoretical significance, but is important in that it is used to derive the sample standard deviation.³⁵

Sample Standard Deviation

The standard deviation of a sample of n measurements is equal to the square root of the variance:

$$s = \sqrt{s^2} = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n-1}} \quad (3)$$

The standard deviation as a measure of data variation is easily interpreted by means of a rule of thumb known as the Empirical Rule.³⁶

The Empirical Rule

If a data set has an approximately mound-shaped relative frequency distribution, then the following rules of thumb may be used to describe the data set:

- Approximately 68% of the measurements will lie within 1 standard deviation of their mean (i.e. within the interval $\bar{y} \pm s$ for samples).
- Approximately 95% of the measurements will lie within 2 standard deviations of their mean (i.e. within the interval $\bar{y} \pm 2s$ for samples).
- Almost all the measurements will lie within 3 standard deviations of their mean (i.e. within the interval $\bar{y} \pm 3s$ for samples).

The percentages given in the rule are only approximate, particularly for the first interval of one standard deviation. The percentage of the total number of measurements that fall within two standard deviations of their mean will usually be quite close to 95%. The Empirical Rule is the result of the practical experience of researchers in many fields who have observed its validity with many different types of data sets.³⁷

³⁵ Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. pp. 30-31.

³⁶ Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. pp. 30-31.

³⁷ Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. p. 31.

Skewness

Skewness characterizes the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values. Negative skewness indicates a distribution with an asymmetric tail extending toward more negative values.³⁸ The equation for skewness is:

$$skewness = \frac{n}{(n-1)(n-2)} \sum_{i=1}^n \left(\frac{x_i - \bar{x}}{s} \right)^3 \quad (4)$$

Kurtosis

Kurtosis characterizes the relative peakedness or flatness of a distribution compared with the normal distribution. Positive kurtosis indicates a relatively peaked distribution. Negative kurtosis indicates a relatively flat distribution.³⁹ The equation for kurtosis is:

$$kurtosis = \left\{ \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum_{i=1}^n \left(\frac{x_i - \bar{x}}{s} \right)^4 \right\} - \frac{3(n-1)^2}{(n-2)(n-3)} \quad (5)$$

Measures of Relative Standing

Measures of relative standing are the third group of numerical descriptive measures. They are a collection of mathematical techniques used to describe the relative position of an observation within the data set. In certain situations, one can gain additional information about an observation based on where it falls in the overall distribution. This section reviews the various measures of relative standing that are used throughout the discrepancy analysis.

Percentile

The $100p^{\text{th}}$ percentile of a data set is a value of y located so that $100p\%$ of the area under the relative frequency distribution for the data lies to the left of the $100p^{\text{th}}$ percentile and the remaining $100(1-p)\%$ of the area lies to its right.⁴⁰ The median of a given data set is its 50^{th}

³⁸ Entire paragraph drawn from *Microsoft Excel 2000 Function Reference*. Redmond, WA: Microsoft Corporation, 2000.

³⁹ Entire paragraph drawn from *Microsoft Excel 2000 Function Reference*. Redmond, WA: Microsoft Corporation, 2000.

⁴⁰ Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. pp. 34-35.

percentile, and the lower and upper quartiles are defined as the 25th and 75th percentiles, respectively. The quartile points, and any percentiles in general, are generally not as crisply defined for small data sets.

Sample Z-Score

The z-score for a value y of a data set is the distance that y lies above or below the mean, measured in units of the standard deviation:

$$z = \frac{y - \bar{y}}{s} \quad (6)$$

By definition, the z-score describes the location of an observation y relative to the mean. Negative z-scores indicate that the observation lies to the left of the mean; positive z-scores indicate that the observation lies to the right of the mean. According to the Empirical Rule, most of the observations in a data set will be less than 2 standard deviations from the mean and will therefore have z-scores less than 2 in absolute value. In addition, almost all observations will be within 3 standard deviations of the mean and will have z-scores less than 3 in absolute value.⁴¹

Outliers

An observation y that is unusually large or small relative to the other values in a data set is called an outlier. Outliers typically are attributable to one of the following causes:

- The measurement is observed, recorded, or entered into the computer incorrectly.
- The measurement comes from a different population.
- The measurement is correct, but represents a rare chance event.

The most obvious method for determining whether an observation is an outlier is to calculate its z-score. Observations with z-scores greater than 3 in absolute value are considered outliers. However, the presence of one or more outliers in a data set can inflate the value of s used to calculate the z-score. Consequently, it will be less likely that an errant observation would have a z-score larger than 3 in absolute value. Another method for determining whether an observation is an outlier is calculating the interquartile range, IQR, which is the difference between the upper and lower quartile values. Observations less than 1.5(IQR)

⁴¹ Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. p. 36.

below the lower quartile, or greater than $1.5(IQR)$ above the upper quartile are suspect outliers. Those less than $3(IQR)$ below the lower quartile, or greater than $3(IQR)$ above the upper quartile are highly suspect outliers. In contrast with z-scores, the values of the quartiles used to calculate IQR are not affected by the presence of outliers.⁴²

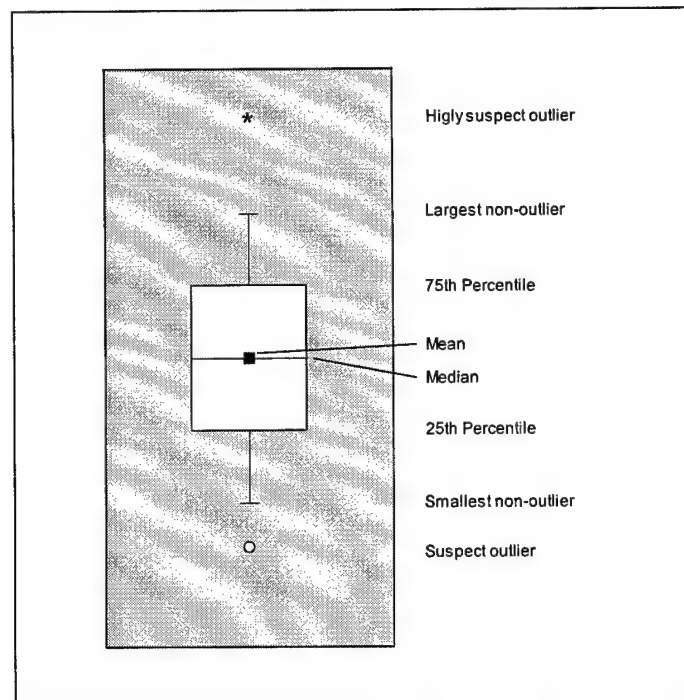
Box Plot

The box plot display is useful for graphically examining the dispersion of the data set. It was designed by John Tukey, and is a graphical display that indicates range, quartiles, inter-quartile range, median, and outliers of a data set. An annotated sketch of a box plot is shown in Figure 6. The bold horizontal line in the middle of the box indicates the sample median. A single filled square designates the sample mean. The edges of each box, called hinges, mark the 25th and 75th percentiles, so that the central 50% of the data values fall within the range of the box. The whiskers, or the vertical lines extending up and down from each box, show the range of values that fall within $1.5(IQR)$ of the hinges. Data points that have values between $1.5(IQR)$ and $3(IQR)$ outside the hinges are marked by an open circle, to designate a suspect outlier. Data points more than $3(IQR)$ below the lower hinge or above the upper hinge are marked by an asterisk, to designate a highly suspect outlier.⁴³

⁴² Entire paragraph drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. pp. 37-39.

⁴³ Entire paragraph drawn from *SPSS Base 10.0 Applications Guide*. Chicago, IL: SPSS, Inc., 1999. pp. 40-41.

Figure 6 – Annotated Diagram of a Box Plot



Measures of Correlation

Measures of correlation are the fourth and final group of numerical descriptive measures used in this study. They are a collection of mathematical techniques used to describe the relationship between two variables in a set of observations. As before, each technique has strengths and weaknesses that make it more useful and accurate in some cases, but not others. The ‘best’ measure of correlation for a given data set depends both on the type of descriptive information desired and the nature of the data being evaluated.

Spearman’s Rank Correlation Coefficient

Since the discrepancy data does not exhibit a normal distribution, a correlation method designed for this type of data must be used. In nonparametric regression, tests of model adequacy do not require any assumptions about the distribution of the random error term; thus, they are distribution-free. Spearman’s rank correlation coefficient can be used to test for correlation between two variables, y and x . It is found by first ranking the values of each

variable separately. Then the coefficient is calculated using the sum of squares of the deviations for the rankings.⁴⁴

The correlation coefficient provides a scaleless quantitative measure of the strength of the linear relationship between x and y . The value of the coefficient is always between -1 and $+1$, regardless of the units of the variables. Values near 0 imply little or no relationship between the variables, while values near -1 or $+1$ indicate a strong relationship. The values of -1 and $+1$ themselves correspond to a situation where all the data points fall exactly on the least squares line. Positive values imply that y increases as x increases; negative values imply that y decreases as x increases.⁴⁵

It is important to note that a strong correlation between two variables does not necessarily imply causality between one and the other. It merely indicates a mathematical relationship between the observed values of one variable and the observed values of the other.

Nonparametric Test for Rank Correlation

It is not enough to state that a correlation exists between two variables of interest. One must also determine the likelihood of a similar correlation occurring by chance. Generally, as the number of observations in the data set increases, the less likely a similar correlation could be found by chance. Therefore, each time the correlation coefficient is calculated, it must be compared to a pre-defined critical value for two-tailed significance. In this study, only correlations larger than the critical value for a two-tailed significance of 0.01 were accepted.

Analysis Method

The data collection procedure outlined earlier in the chapter resulted in a database of over $9,200$ discrepancies, all categorized according to related subsystem and root cause. In addition, each spacecraft was categorized by several unique design parameters, which then became associated with the corresponding discrepancies for that spacecraft. This section

⁴⁴ Portions drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. p. 784.

⁴⁵ Portions drawn from Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. p. 441.

describes the steps taken to analyze the compiled data set and obtain the results presented in Chapter 6.

Category Relative Frequency

For data that is divided into discrete groups or categories, the category relative frequency is the proportion of the total number of observations that fall into each category.⁴⁶ This is the case with discrepancy data when categorized according to affected subsystem and root cause. The category relative frequency diagram is similar to a histogram, which is used to depict absolute or relative frequencies of numerically based data.

Two category relative frequency diagrams were created for the subsystem analysis, one diagram showing the number of discrepancies occurring in each individual subsystem, and the second diagram showing the number of discrepancies occurring in spacecraft subsystems vice infrastructure-related subsystems. The few database entries that were associated with multiple subsystems were excluded from this depiction, since each observation must fall into one and only one category.

Spacecraft Normalization

As mentioned previously, operations facilities have their own procedures for recording discrepancy data. This leads to large variations in the number of discrepancies provided by each organization as well as the detail provided in each report entry. This can be problematic when merging the reports into one data set for analysis, since organizations that contribute smaller data sets tend to get lost in the noise of organizations that contribute very large quantities of reports. In addition, the presence of one very large and unique data set can potentially skew the results of the entire study.

One solution to this problem, and the one chosen for use here, is to normalize the discrepancy data on the basis of each spacecraft. This is accomplished by dividing the number of discrepancies associated with each subsystem or cause for a given spacecraft by the sum total of the spacecraft's discrepancies. The resulting data observations for the spacecraft are a set

⁴⁶ Mendenhall, William and Terry Sincich. *Statistics for Engineering and the Sciences*. 3rd ed. San Francisco, CA: Dellen Publishing Company, 1992. p. 14.

of percentages, one for each subsystem or cause, which describes the distribution of problems among the various categories.

Figure 7 is an example database display for a notional spacecraft. It shows how the various design elements are recorded for each spacecraft, and how the number of discrepancy reports in each associated subsystem category and root cause category is reported. As an example, the normalized percentage score of the Communications Relay subsystem for the notional spacecraft in Figure 7 would be $110 / 300 = 37\%$.

Figure 7 – Database Display for Notional Spacecraft

Spacecraft ID

3

Organization ID

C

Mission

Remote Sensing

Comm

Multiple Dedicated GS

Altitude

Low

Orbit

Other

Altitude

Three-Axis Stabilized

Complexity

Medium

Multiple

No

Number of Discrepancies per Subsystem Category

	Total	Admin	Comm	DMS	EPDS	Facilities	GNC	Ground	Other Inf	Overa
	300	15	110	30	10		15	60		

Number of Discrepancies per Root Cause Category

	Total	Design	Equipment	Interference	Material	No Anomaly	Operator
	300	15	50	25	10	30	25

Record: 3 of 11

Percentile Rankings

The result of the normalization process is a list of percentages representing the fraction of discrepancies for each spacecraft that are associated with each subsystem category. Table 1 is a notional depiction of a portion of the normalized discrepancy data.

Table 1 – Normalized Discrepancy Data for Notional Spacecraft

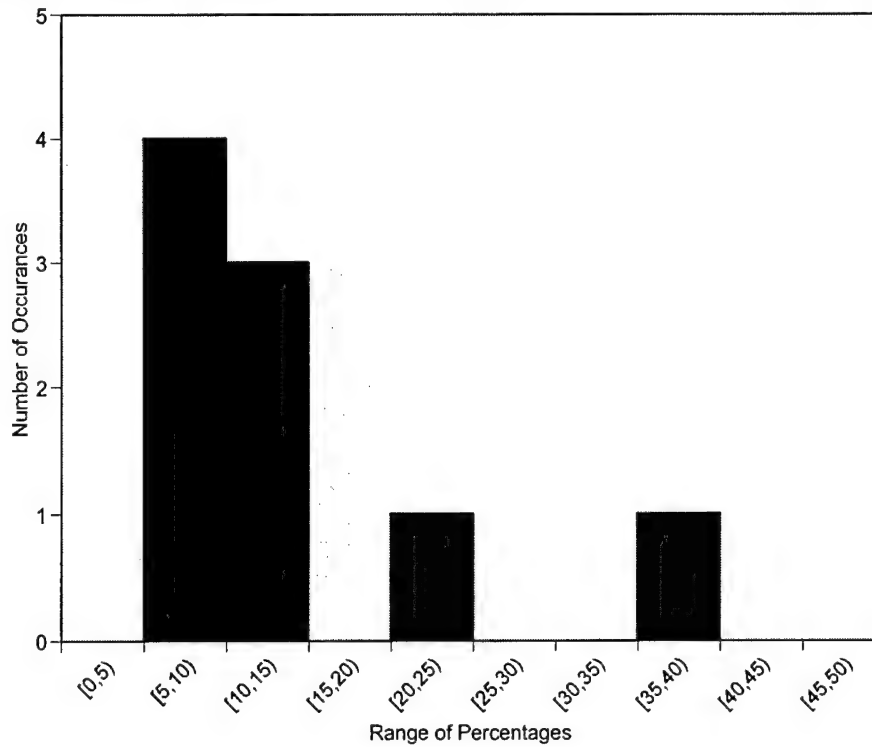
Spacecraft	Ground System	Comm Relay	DMS	Payload	• • •
1	35%	5%	20%	5%	
2	25%	25%	20%	0%	
•	20%	37%	10%	5%	
•	80%	10%	0%	0%	

Note that for the actual normalized data set, the list includes all spacecraft in the database and all subsystem categories used in the study. Each complete row sums to 100% – representing the total discrepancies for a given spacecraft. Meanwhile, each column can be analyzed to determine whether or not the particular subsystem is consistently identified as a problem across multiple spacecraft programs. Thus, the column of percentage scores for each subsystem becomes the basis of the statistical analysis described next. The root cause category percentage rankings are treated in a similar fashion.

Statistical Measures

When the column of subsystem percentage scores becomes the basis of analysis, a histogram is used to show the number of observations that fall within each range of percentage values. Figure 8 is an example of such a histogram for a set of notional observations in the Communications Relay subsystem. The example value calculated above, 37%, appears in the figure as the only observed value falling in the range of 35 – 40%.

Figure 8 – Notional Histogram of Percentage Scores for the Comm Relay Subsystem



The set of observations depicted in Figure 8 can be analyzed using the statistical techniques described above. The resulting parameters, shown in Table 2, specify that the sample mean is 14.41%. This indicates that on average, 14.41% of the discrepancies reported for each spacecraft in the data set were associated with the communications subsystem.

Table 2 – Statistical Parameters for Notional Comm Relay Subsystem

	Mean	Median	Trim Mean	Max	Min	Range	Variance	Std Dev	Skewness	Kurtosis
Comm Relay	0.1244	0.1000	0.1244	0.3700	0.0500	0.3200	0.0125	0.1118	1.7349	2.2968

The other parameters in Table 2 offer additional insight. The sample median, 10%, reflects that a large number of observations in the data set were less than the sample mean. This is supported by the skewness value, which represents a distribution with a longer right (positive) tail.

One disadvantage to the normalization process is that it reduces an extremely large data set of discrepancy reports down to a data set with the same number of observations as the

number of spacecraft. Although a reduced data set is easier to deal with computationally, the smaller sample size can make statistical parameters less representative.

Correlation Analysis

The final step of the analysis is to check for correlations between the spacecraft design elements listed in Chapter 4 and the type of discrepancies that occur during operations. The normalized discrepancy data, similar to that shown in Table 1, is first grouped according to like values for one particular design element of interest, for example mission type. The groupings are then arranged in ascending order and ranked. Likewise, the percentages of discrepancies for a subsystem of interest, like communications relay, are also ranked. Spearman's rank correlation coefficient is then calculated for the two sets of rankings and compared to the critical value for two-tailed significance.

This process was repeated for each combination of design element and subsystem category and each combination of design element and root cause category. Combinations with a Spearman's rank correlation coefficient greater than the critical value are reported in Chapter 6, while those weaker than the critical value were discarded.

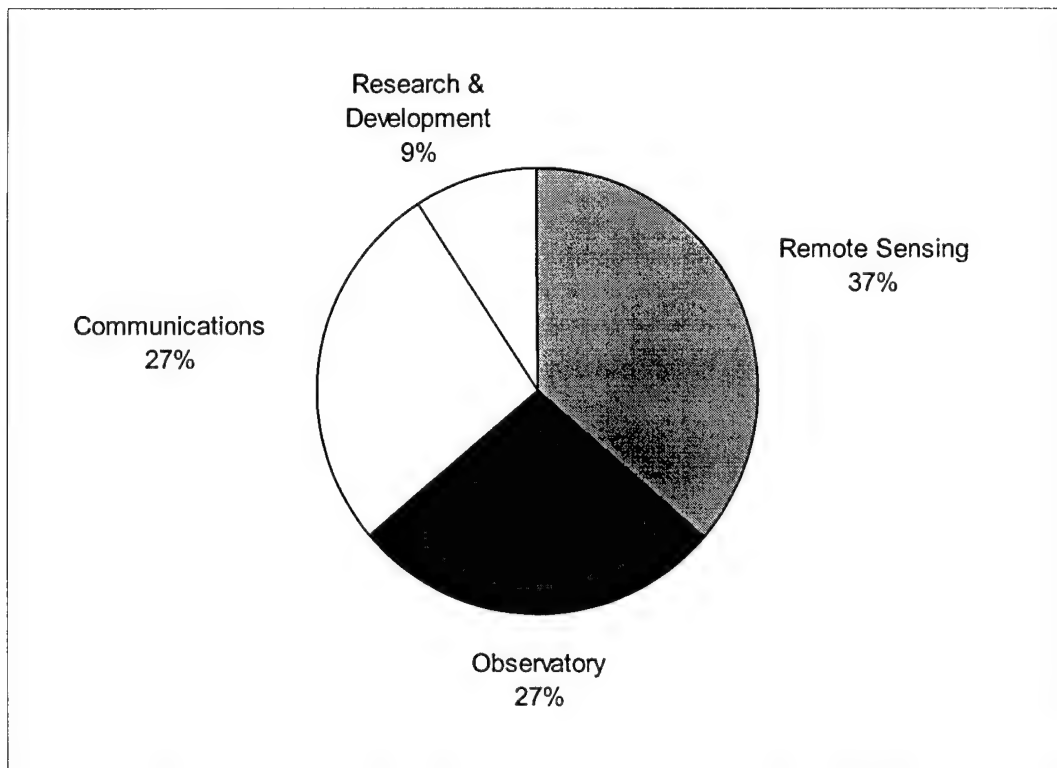
Chapter 6 – Results

This chapter presents the results of the analysis described in Chapter 5 when applied to the discrepancy database. The general characteristics of the data are reviewed first, followed by the results pertaining to each hypothesis. Additional observations based on the root cause information are presented at the end of the chapter.

Review of Data

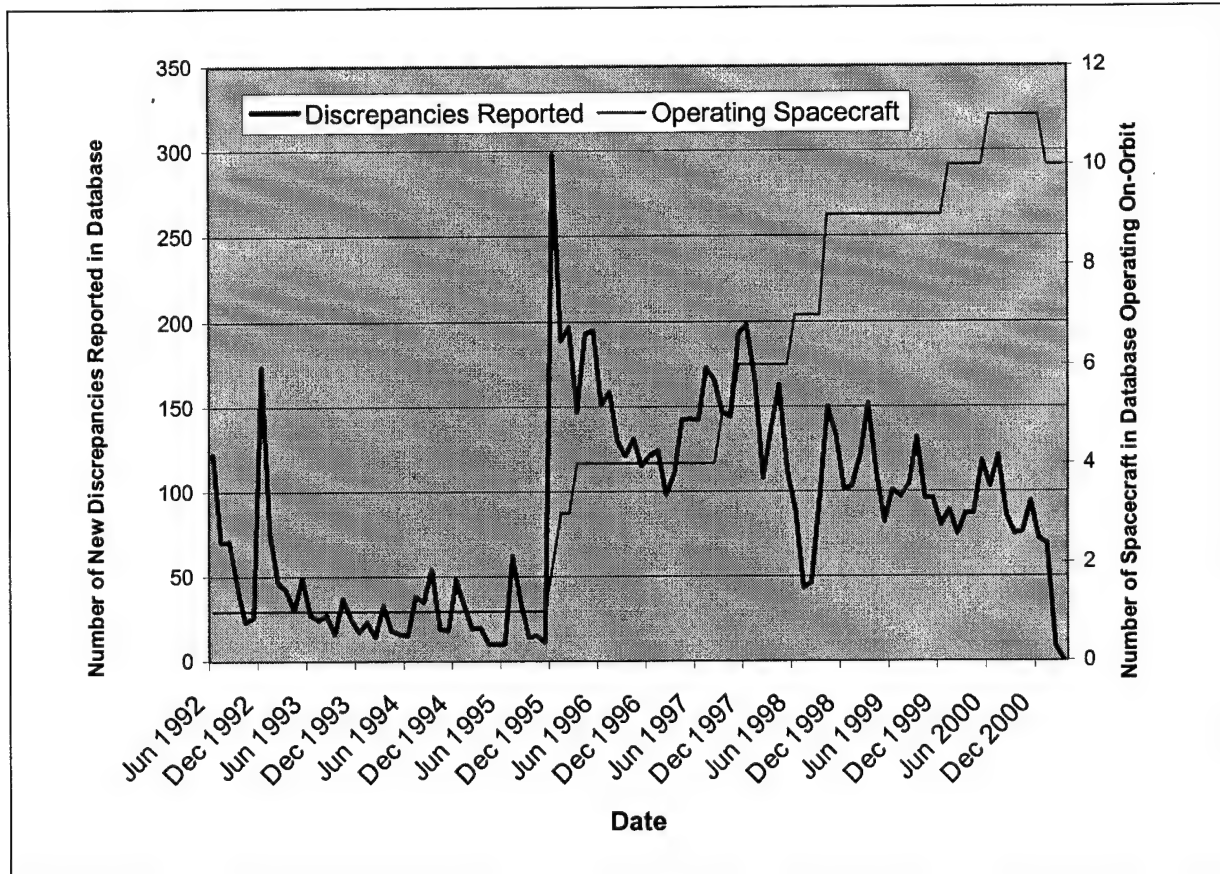
The database compiled for this study consisted of over 9,200 discrepancy reports collected during operation of 11 on-orbit spacecraft. The mission areas represented by the satellites in the study included communications, remote sensing, research and development, and observatories. The breakdown of mission areas is depicted graphically in Figure 9.

Figure 9 – Breakdown of Spacecraft by Mission Area



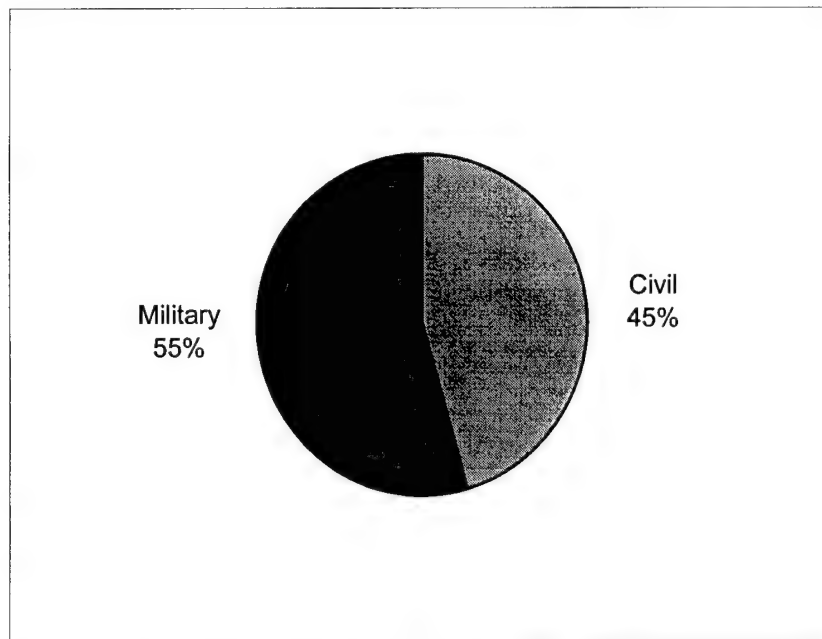
The dates on which the discrepancies occurred ranged from June 1992 to March 2001. The distribution of discrepancies as well as the number of operational spacecraft in the database throughout the time period is shown in Figure 10.

Figure 10 – Distribution of Discrepancies Reported by Date



Several civil and military organizations contributed data for this analysis. The breakdown of all spacecraft according to the organizations responsible for operating them is depicted graphically in Figure 11. It is important to note that there are no commercial systems represented in this study.

Figure 11 – Breakdown of Spacecraft by Responsible Organization

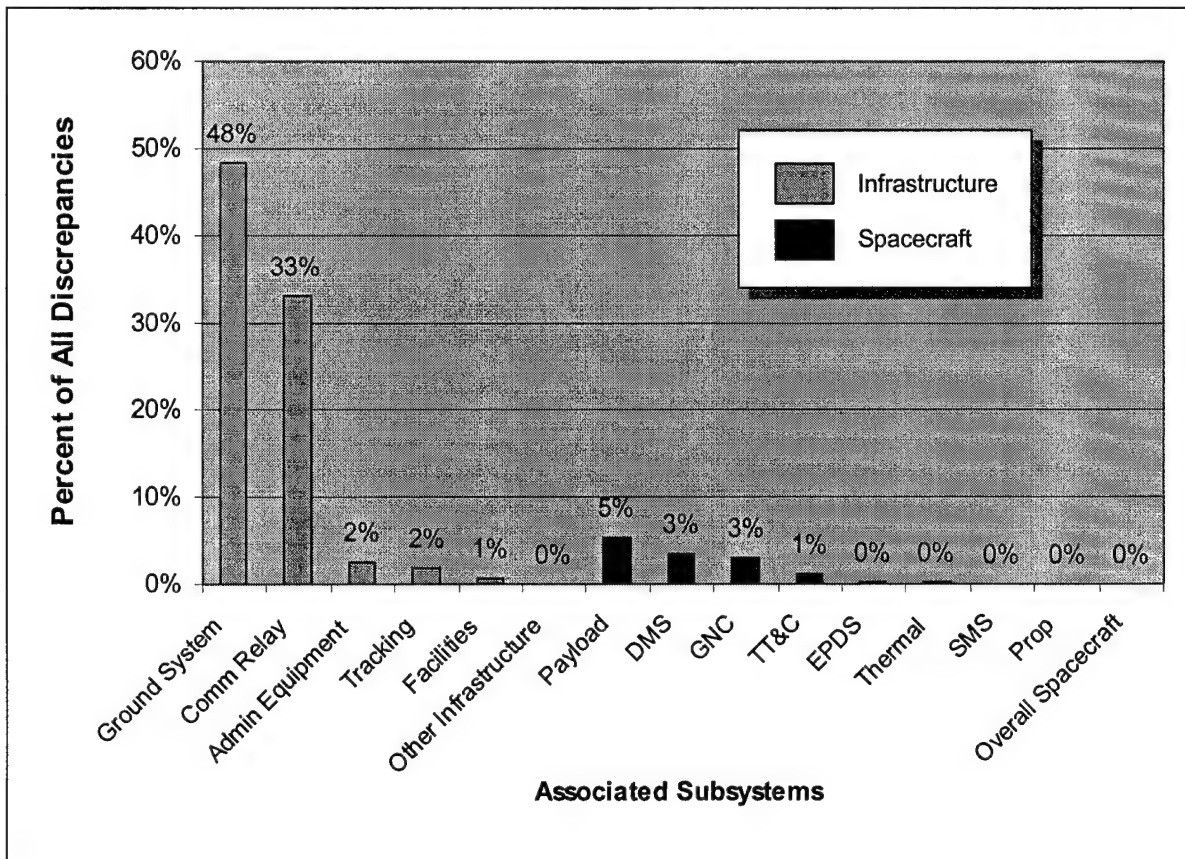


The nature and validity of the sampling of spacecraft included in this study is discussed further in Chapter 7.

First Hypothesis

The first hypothesis proposed in this study was that most problems encountered by an operator do not involve the spacecraft at all, but are attributed to other elements of the space system. The most direct way to address the issue is to report the number of discrepancies belonging to each subsystem category. This is accomplished with the category relative frequency diagram shown in Figure 12. The diagram indicates that the two subsystems most frequently associated with discrepancies are ground systems and communications relays.

Figure 12 – Percentage of All Discrepancies Reported vs. Associated Subsystem



The next step is to group the various subsystems according to whether they are located on the spacecraft or within the operational infrastructure. The subsystems located on, or associated with, the spacecraft include: EPDS, GNC, payload, propulsion, SMS, DMS, TT&C, thermal, harness, other spacecraft, and spacecraft. The subsystems considered part of the operational infrastructure include: ground systems, communications relay, tracking equipment, facilities, administrative equipment, and other infrastructure. Detailed explanations of the individual categories can be found in Chapter 4. The percentage of all discrepancies reported against each major grouping – spacecraft or infrastructure – is shown in the category relative frequency diagram in Figure 13.

Figure 13 – Percentage of All Discrepancies Reported by Major Grouping

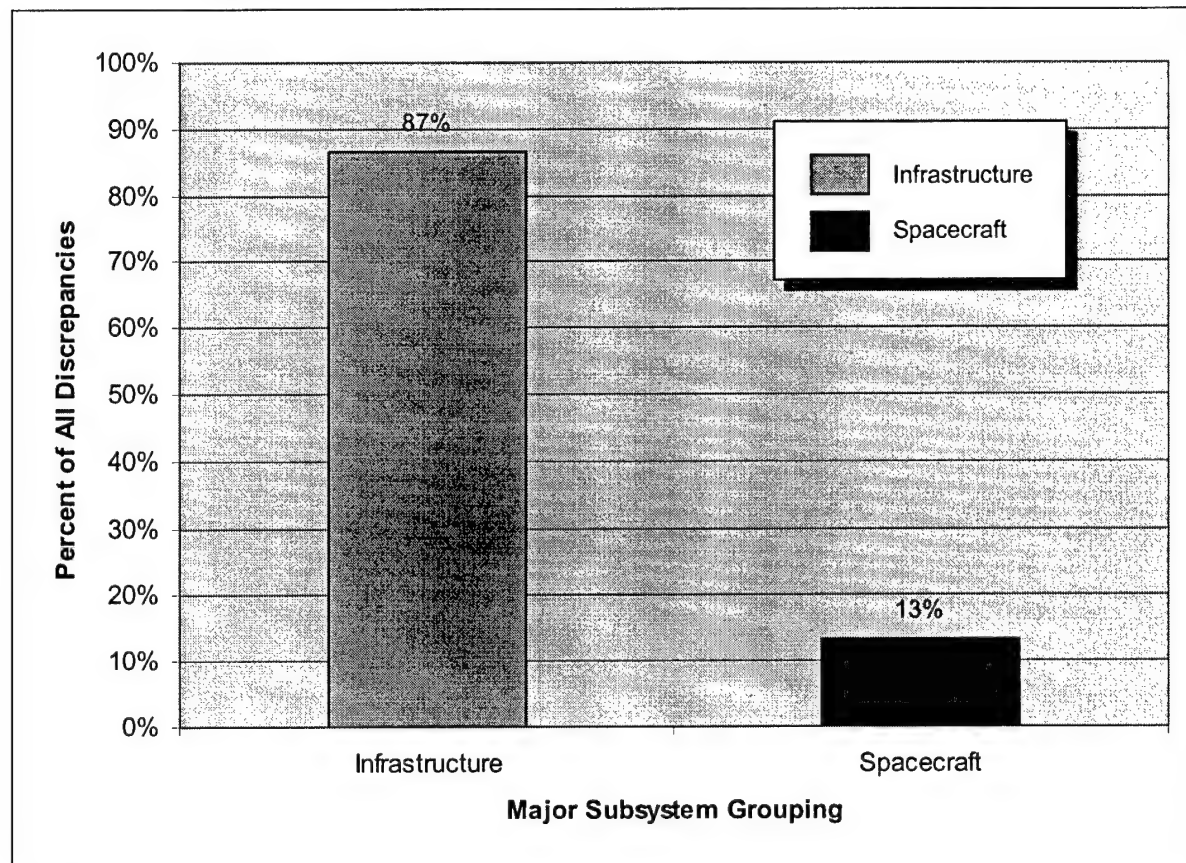


Figure 13 shows that 87% of all discrepancies are associated with subsystems found in the operational infrastructure, a clear majority that tends to support the hypothesis. However, the category relative frequency diagram can be skewed if one or two outlier spacecraft have an uncommonly large number of discrepancies associated with infrastructure. The normalization process outlined in Chapter 5 is designed to overcome this limitation and provide a more accurate representation of the data set.

The result of the normalization process is a list of percentages representing the fraction of discrepancies for each spacecraft that are associated with each subsystem category. The percentages in each column can be analyzed to determine whether or not the particular subsystem is consistently identified as a problem across multiple spacecraft programs. The statistical parameters described earlier in Chapter 5 are used for this purpose. Table 3 shows

the resulting statistics for each subsystem against which at least one discrepancy was reported.

Table 3 – Resulting Statistics for Each Subsystem⁴⁷

	Mean	Median	Trim Mean	Max	Min	Range	Variance	Std Dev	Skewness	Kurtosis
Ground System	0.6578	0.8378	0.6578	0.9450	0.2058	0.7392	0.0997	0.3157	-0.6623	-1.7746
Comm Relay	0.1663	0.1053	0.1663	0.5297	0.0018	0.5279	0.0241	0.1551	1.6340	2.2500
Admin Equipment	0.0281	0.0435	0.0281	0.0504	0.0000	0.0504	0.0005	0.0212	-0.5104	-1.8422
Tracking	0.0136	0.0000	0.0136	0.0740	0.0000	0.0740	0.0006	0.0247	1.9094	2.9946
Facilities	0.0038	0.0000	0.0038	0.0129	0.0000	0.0129	0.0000	0.0052	0.8267	-1.2694
Other Infrastructure	0.0144	0.0000	0.0144	0.1579	0.0000	0.1579	0.0023	0.0476	3.3166	11.0000
Payload	0.0200	0.0000	0.0200	0.0865	0.0000	0.0865	0.0010	0.0314	1.3630	0.4639
DMS	0.0459	0.0000	0.0459	0.2105	0.0000	0.2105	0.0059	0.0768	1.5572	1.1334
GNC	0.0218	0.0000	0.0218	0.1540	0.0000	0.1540	0.0022	0.0470	2.6472	7.3777
IT&C	0.0221	0.0000	0.0221	0.1053	0.0000	0.1053	0.0014	0.0373	1.5197	1.1234
EPDS	0.0034	0.0000	0.0034	0.0193	0.0000	0.0193	0.0001	0.0072	1.9462	2.2793
Thermal	0.0014	0.0000	0.0014	0.0072	0.0000	0.0072	0.0000	0.0027	1.7935	1.7522
SMS	0.0008	0.0000	0.0008	0.0054	0.0000	0.0054	0.0000	0.0018	2.2433	4.2997
Prop	0.0003	0.0000	0.0003	0.0032	0.0000	0.0032	0.0000	0.0010	3.2982	10.9074
Overall Spacecraft	0.0003	0.0000	0.0003	0.0032	0.0000	0.0032	0.0000	0.0010	3.3166	11.0000

Table 3 contains a great deal of information about each subsystem category. Using the first row as an example, an average 65% of discrepancies reported for a given spacecraft are associated with the ground system. The median value indicates that there is a fairly large concentration of spacecraft in the sample for which the ground system accounts for a large number (~84%) of discrepancies. The maximum, minimum, and skewness values indicate that at least one spacecraft with a low number of ground system problems (~21%) is pulling down the mean and skewing the distribution of percentages downward.

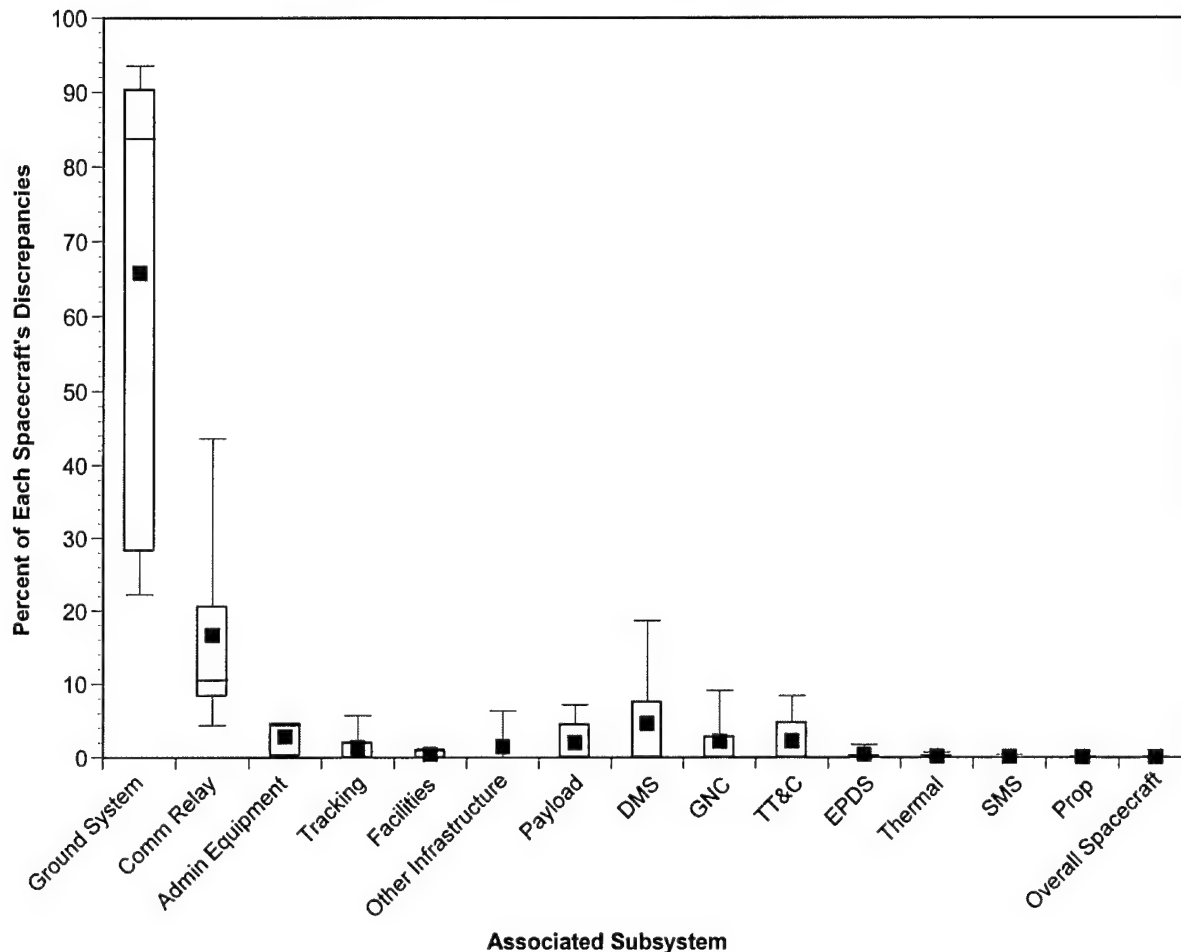
Unfortunately, the detailed information shown in Table 3 is difficult to visualize and interpret. Similar information can be presented graphically in the form of a box plot. Figure 14 shows the distribution of percentages for each subsystem category using a box plot.

It is less obvious in Figure 14 than in Figure 13 that the operational infrastructure accounts for a much larger percentage of discrepancies than spacecraft subsystems. However, it gives

⁴⁷ Only subsystem categories with at least one discrepancy reported are shown in this table. The values listed in the first five columns are decimal percentages.

a more accurate presentation of the fact that two elements of the operational infrastructure in particular – ground systems and communications relays – are consistently attributed to discrepancies across several different spacecraft programs.

Figure 14 – Box Plot of Subsystem Statistics



Second Hypothesis

The second hypothesis proposed in this study was that correlations exist between aspects of a space system design and the nature of problems experienced by the operations staff over the long term. To address this question, correlation tests were conducted for each combination of design element and subsystem category. Combinations with a Spearman's rank correlation coefficient greater than the critical value are reported below, while those weaker than the critical value were discarded.

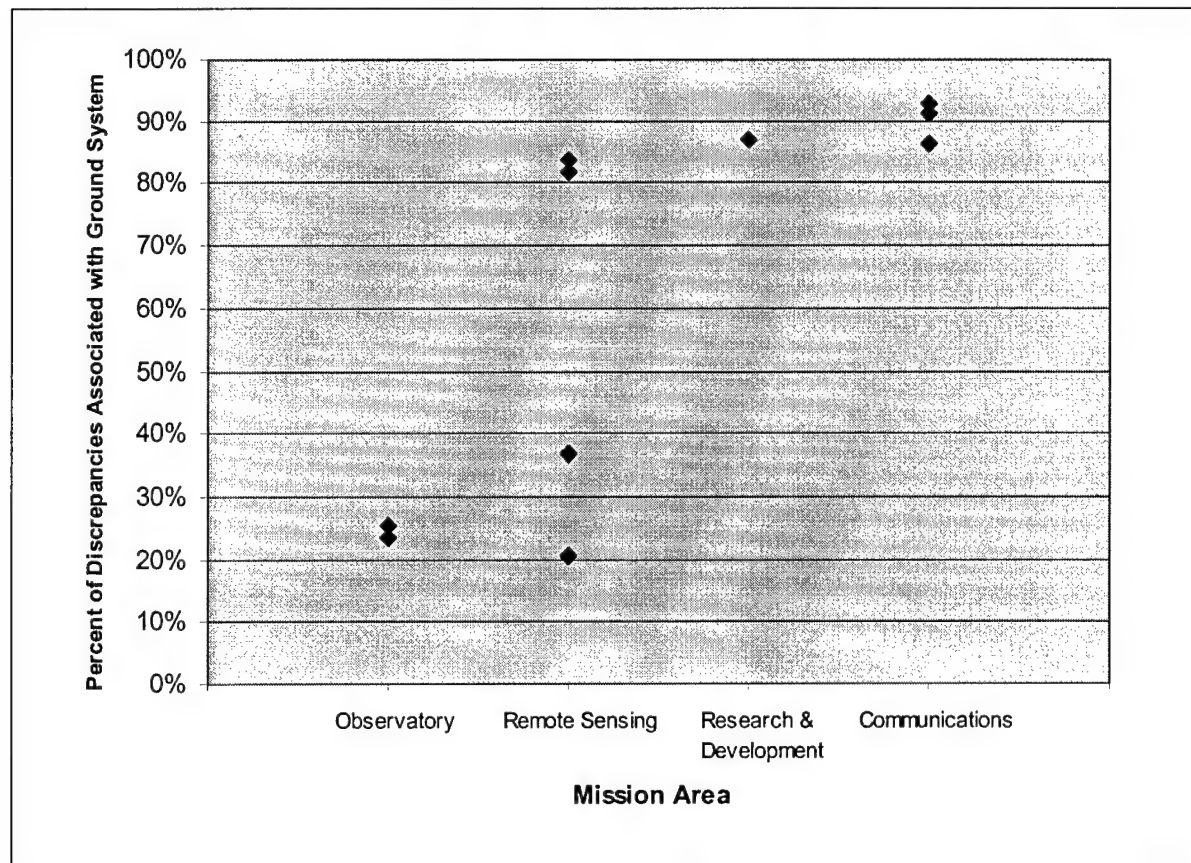
The correlations between most of the subsystem categories were not statistically significant based on the sample size and the number of discrepancies reported for each category. Two subsystem categories, in particular, did display a strong correlation with elements of the spacecraft design: ground system and communications relay. The percentage of each satellite's discrepancies associated with each of these two subsystems is listed in Table 4.

Table 4 – Percent of Each Satellite's Discrepancies Associated with Ground System and Comm Relay

	1	2	3	4	5	6	7	8	9	10	11
Ground System	37%	23%	21%	84%	82%	93%	91%	87%	86%	25%	94%
Comm Relay	11%	23%	37%	14%	13%	7%	9%	9%	8%	53%	0%

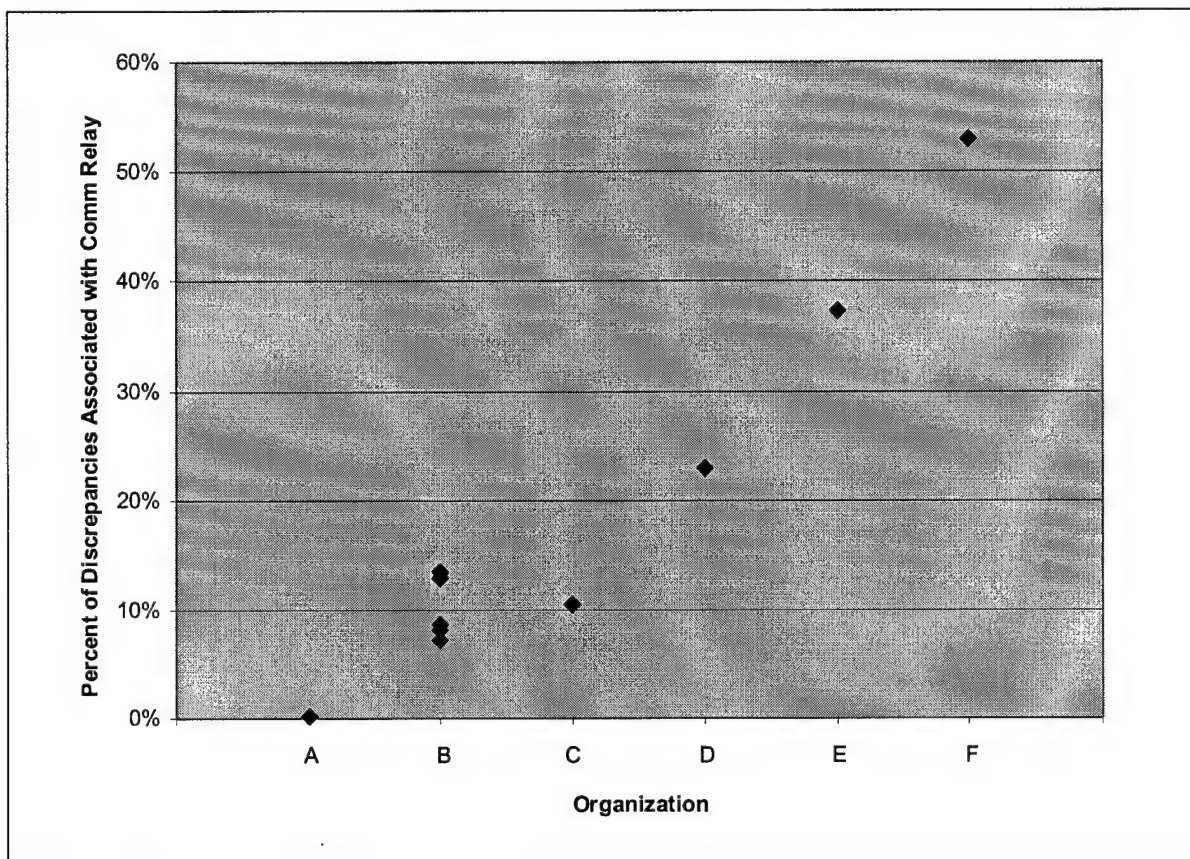
The first correlation presented here is between the mission type of the spacecraft and the percentage of its discrepancies associated with the ground system. The Spearman's rank correlation coefficient for this relationship is 0.852. Figure 15 shows the percentage of discrepancies associated with the ground system reported by each spacecraft plotted against the mission type of the spacecraft. The correlation indicates that the percentage of problems associated with the ground system generally changes given a certain mission type. In other words, spacecraft performing certain missions tend to experience ground system problems more frequently than spacecraft performing other missions. However, it is important to note that the presence of a correlation does not imply that certain spacecraft mission types *cause* a larger percentage of ground system problems than others.

Figure 15 – Ground System Discrepancies per Spacecraft vs. Mission Type



The second correlation presented here is between the organization and the percentage of discrepancies associated with the communications relay. The Spearman's rank correlation coefficient for this relationship is 0.850. Figure 16 shows the percentage of discrepancies associated with the communications relay reported by each spacecraft plotted against the organization responsible for operating the spacecraft. In this case, organization refers to a group or team that operates one or more spacecraft. The correlation indicates that the percentage of problems associated with the communications relay generally changes from one organization to another. Once again, it is important to note that the presence of a correlation does not imply causality.

Figure 16 – Communications Relay Discrepancies per Spacecraft vs. Organization



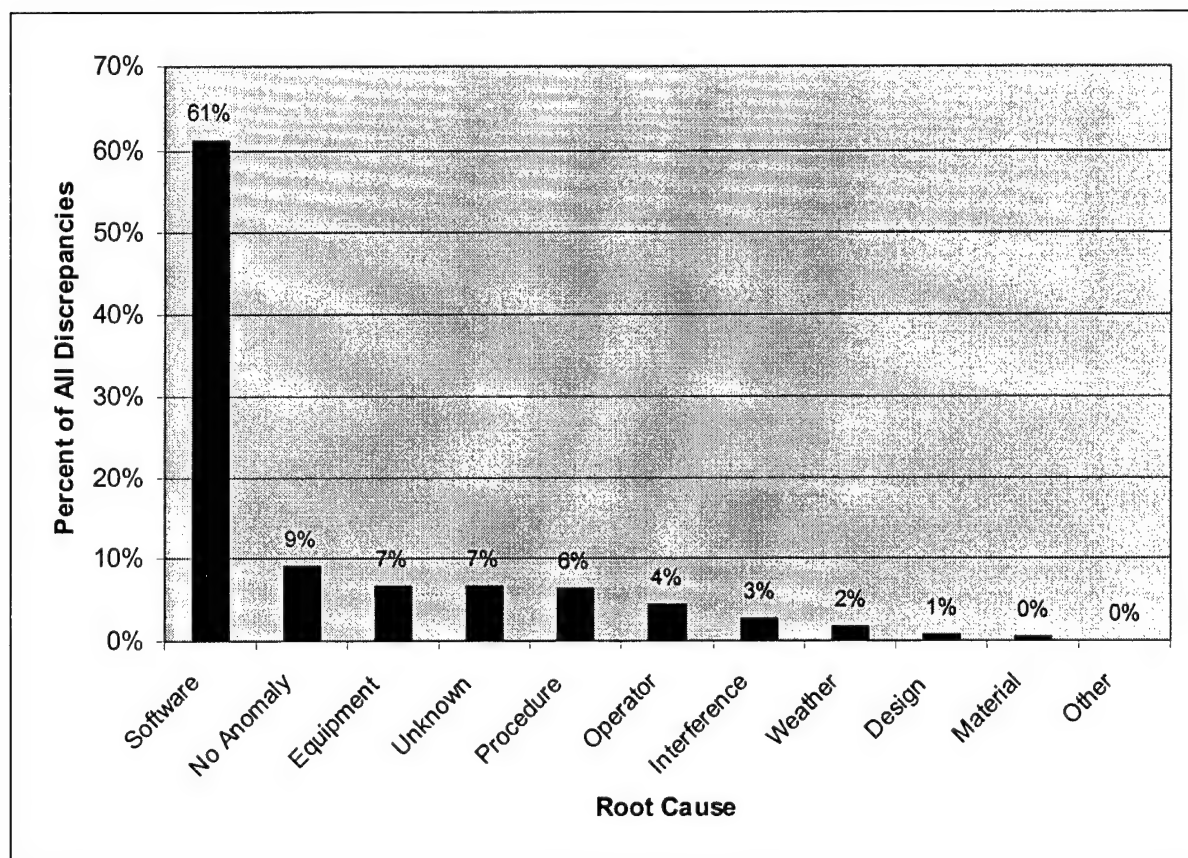
Thus, the data support the second hypothesis, in that a mathematical relationship exists between certain spacecraft design elements and the nature of operational problems experienced in the long run. However, the analysis cannot be considered exhaustive, due to the presence of multiple variables and a sample set which does not fully explore the values for each variable in an independent fashion. This issue is discussed further in Chapter 7.

Additional Observations

Most of the discrepancy data sets contributed for this study contained root cause information in each report. Those that did not were excluded from this portion of the analysis. In a similar fashion as the subsystem category, the first step is to report the number of discrepancies belonging to each subsystem category. This is accomplished with the category relative frequency diagram shown in Figure 17. The diagram indicates that software problems are the most frequent cause of discrepancies, occurring in 61% of the reported

cases. The equipment, unknown, procedure, and no anomaly categories were comparable at approximately 7% each. As a reminder, “software problems” are defined as discrepancies caused by software, either on the spacecraft or on the ground equipment. Includes problems caused by hung processes, or instances where a computer reboot is required to restore functionality. Categories not shown on the graph were not reported on any of the discrepancies in the data set.

Figure 17 – Percentage of All Discrepancies Reported vs. Root Cause



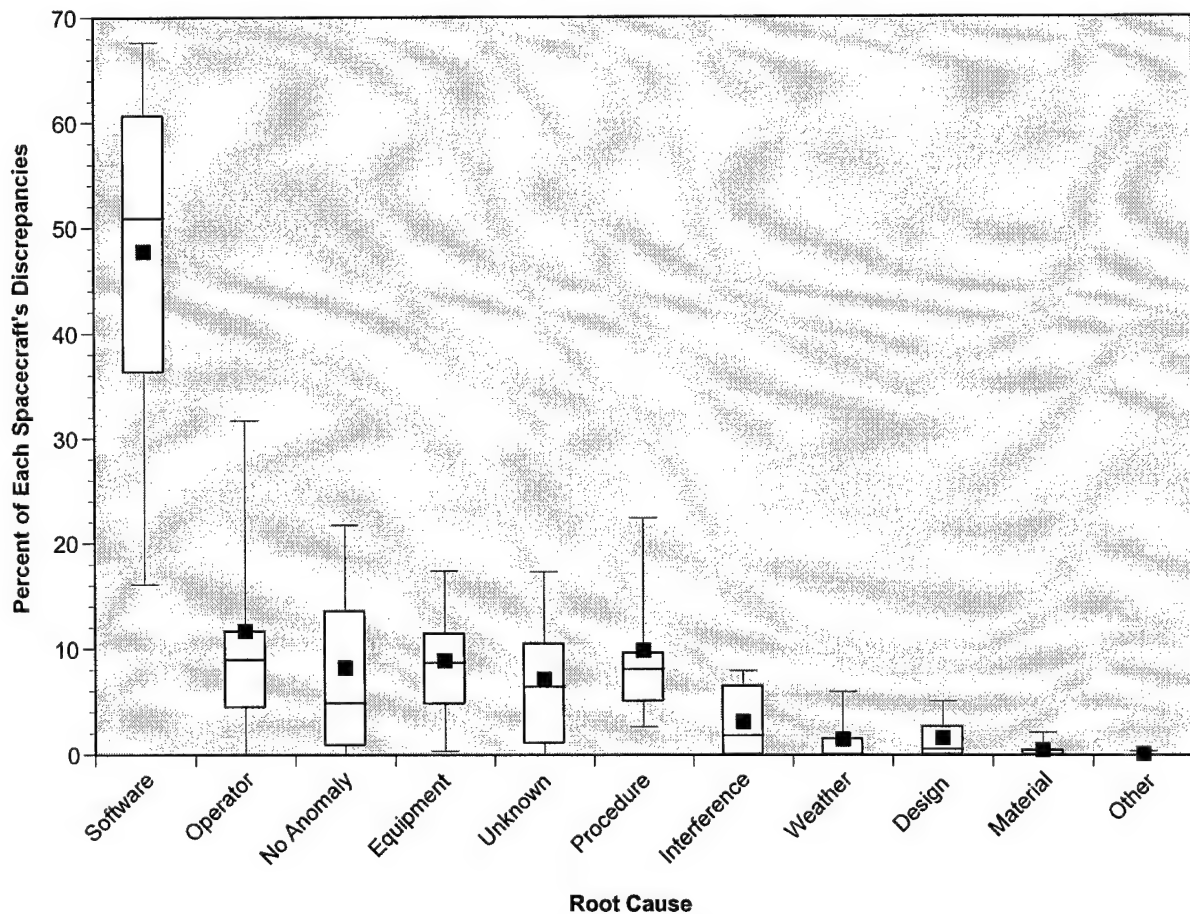
The normalization process can also be applied to the root cause analysis to prevent one or two spacecraft from skewing the results. When the data is normalized on a per-spacecraft basis, the resulting statistical parameters for each root cause category are summarized below in Table 5. To make the data in Table 5 easier to interpret, it is shown graphically using a box plot in Figure 18. The diagram shows that software is the only root cause category

consistently reported as a frequently occurring problem among all of the spacecraft in the data set.

Table 5 – Resulting Statistics for Each Root Cause⁴⁸

	Mean	Median	Trim Mean	Max	Min	Range	Variance	Std Dev	Skewness	Kurtosis
Software	0.4773	0.5091	0.4773	0.7585	0.0526	0.7059	0.0405	0.2012	-0.9678	0.7440
No Anomaly	0.0818	0.0489	0.0818	0.2174	0.0000	0.2174	0.0066	0.0812	0.7787	-0.6500
Equipment	0.0884	0.0870	0.0884	0.1739	0.0000	0.1739	0.0034	0.0579	-0.0853	-0.5240
Unknown	0.0800	0.0850	0.0800	0.1739	0.0000	0.1739	0.0035	0.0588	0.3169	-0.5798
Procedure	0.0713	0.0743	0.0713	0.1273	0.0129	0.1144	0.0010	0.0313	-0.2556	0.4560
Operator	0.1167	0.0900	0.1167	0.5789	0.0000	0.5789	0.0257	0.1602	2.8122	8.6573
Interference	0.0309	0.0182	0.0309	0.0868	0.0000	0.0868	0.0011	0.0334	0.6505	-1.2377
Weather	0.0144	0.0000	0.0144	0.1196	0.0000	0.1196	0.0013	0.0357	3.0611	9.6732
Design	0.0158	0.0056	0.0158	0.0541	0.0000	0.0541	0.0004	0.0200	1.0992	-0.0934
Material	0.0045	0.0000	0.0045	0.0236	0.0000	0.0236	0.0001	0.0085	1.8793	2.1706
Other	0.0008	0.0000	0.0008	0.0091	0.0000	0.0091	0.0000	0.0027	3.3166	11.0000

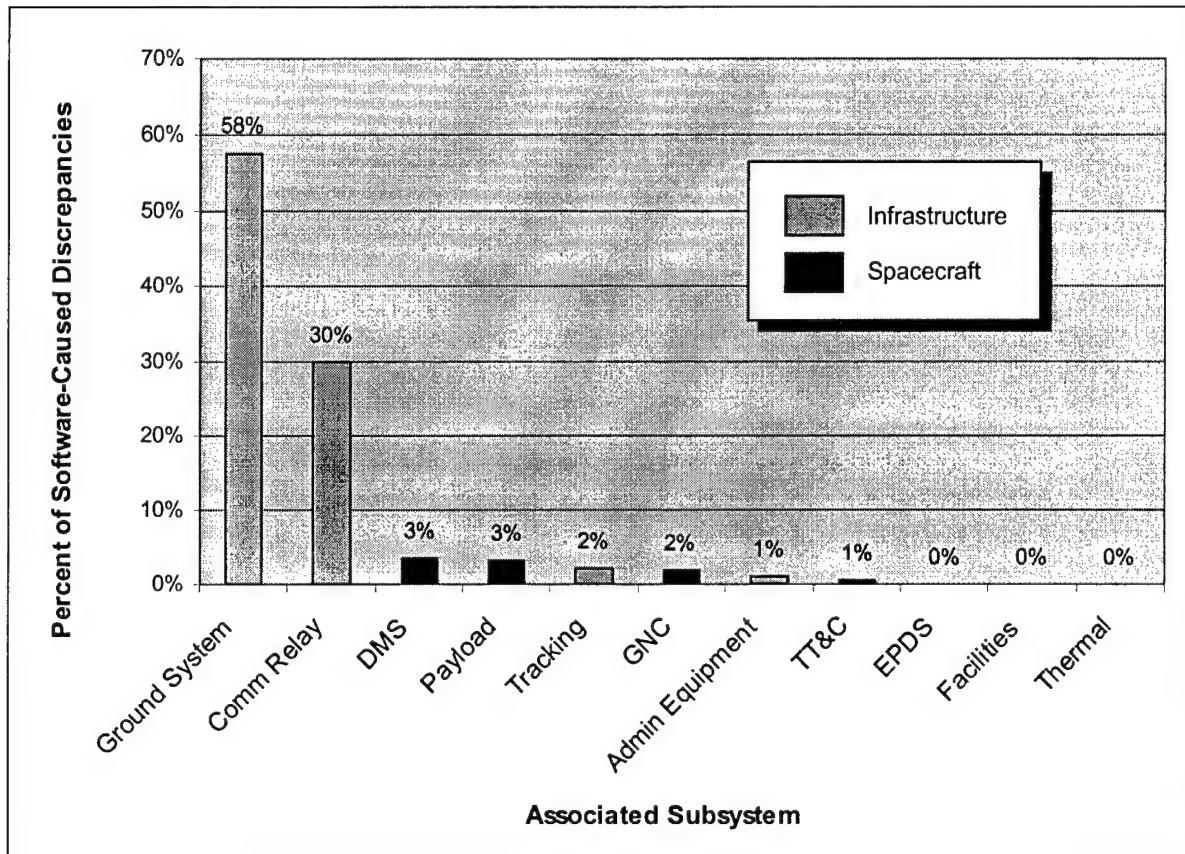
Figure 18 – Box Plot of Root Cause Statistics



⁴⁸ Only root cause categories with at least one discrepancy reported are shown in this table. The values listed in the first five columns are decimal percentages.

Figure 19 provides more insight into the nature of discrepancies documented as caused by software. Over half of the discrepancies caused by software occur in one of the ground system components. All told, 91% are associated with components in the infrastructure and 9% are associated with components on board the spacecraft.

Figure 19 – Associated Subsystems for Discrepancies Caused by Software



The root cause analysis provides insight as to the various sources of discrepancies reported from several organizations. Additional discussion concerning these results is included in Chapter 7.

Chapter 7 – Discussion and Conclusions

Several aspects of the results presented in Chapter 6 are analyzed in this chapter. The first section is an overview of the costs of discrepancies. The second section is a discussion of the data sampling technique and the methodology used in this study, as well as general observations about the data collected. The final section summarizes the analysis and presents several recommendations for the use and future extension of this research.

Cost of Discrepancies

Although the occurrences of discrepancies are well documented within most organizations, the associated costs of dealing with those discrepancies are rarely collected. There are several reasons why this is the case:

- **Cost information does not come from one source.** Discrepancy cost information typically includes the number of labor hours that several different individuals spend in engineering meetings and working groups; the number of labor hours a handful of individuals spend researching, troubleshooting, and repairing; and the direct expenses for equipment and materials. In order to get a complete and accurate representation of discrepancy costs, everyone and everything involved in the process must be accounted for.
- **Ambiguous nature of discrepancy costs.** The delineation between work necessary to accomplish a routine task and work spent troubleshooting a specific problem is difficult to establish in a formal fashion. In some cases, operators may expend significant effort troubleshooting a problem before the associated discrepancy report is even written. In addition, work spent troubleshooting one particular problem sometimes serves to correct one or more other problems. Trying to assign cost to multiple discrepancies can be difficult and subjective.
- **Lack of reporting mechanism.** Even if individual employees track the effort they expend on discrepancies, there must be a mechanism in place to record and collect the

information. Accounting systems in commercial organizations are usually designed to collect cost data on a contract basis, rather than a functional basis. Government organizations – whose employees are salaried – rarely collect labor data at all, and have no infrastructure in place to do so.

- **Cost of collecting cost data itself.** Tracking, recording, reporting, and compiling cost information takes time and effort. As the number of functional tasks (including discrepancies) and the number of employees increase, the work necessary to collect cost data also increases. For larger organizations, it can easily require one or more full-time employees just to deal with the information. Most organizations choose, justifiably, not to pay this additional cost.
- **No desire or need for discrepancy cost data.** In some organizations, troubleshooting problems is considered part of the job, so there is no need to determine exactly how much effort is spent resolving problems versus effort spent performing routine duties. In addition, discrepancy cost data is not useful when an organization does not even track the discrepancies themselves.

Despite the lack of explicit discrepancy cost information, it is possible to estimate the cost of dealing with problems. Interviews with the operational supervisors in two of the participating organizations yielded fairly consistent estimates of the labor required to troubleshoot a problem. Those estimates are used in the following cost analysis.

Generally, discrepancies can be divided into two categories: repetitive or relatively insignificant problems, and significant problems. The percentage of significant problems is roughly equal to the percentage of spacecraft-related problems encountered on-orbit.⁴⁹ Using this rule of thumb for all of the spacecraft included in this study, approximately 1200 problems were considered significant and the remaining 8000 were routine.

⁴⁹ Most spacecraft-related problems are – or are treated as – significant. Repetitive spacecraft-related problems, once well characterized, tend to receive more cursory treatment or are dealt with using contingency procedures. Therefore, they can be considered routine. However, the non-spacecraft infrastructure also occasionally experiences significant problems that must be accounted for. Thus, the percentage of problems that are spacecraft-related is a good approximation for the percentage of problems that are significant.

Routine problems are typically dealt with first in a daily or weekly status meeting with 6–10 people in attendance. The group review takes approximately 10 minutes per discrepancy, and the problem will be assigned to one or two individuals to investigate and/or resolve. The average time spent researching, troubleshooting, and resolving a particular problem and implementing the solution is 8 hours, at which point the results will be reviewed at the status meeting for another 10 minutes before being closed. This yields a fully burdened per-discrepancy cost, not including equipment or materials, of:

$$\left[(2 \text{ meetings}) \times \left(\frac{8 \text{ people}}{\text{meeting}} \right) \times \left(\frac{0.167 \text{ hours}}{\text{person}} \right) + (8 \text{ hours}) \right] \times \left(\frac{\$75}{\text{hour}} \right) \cong \$800 \quad (7)$$

Significant problems, on the other hand, usually involve immediate diagnosis, safing, notification, and documentation by at least one operator and one on-call engineer for approximately 3 hours each. The status meeting attendees receive an initial briefing on the situation for approximately 20 minutes. A team of 4–6 individuals spends roughly 8 hours each, not necessarily consecutive, researching and troubleshooting the problem and developing a solution. Two people each spend an additional 3 hours implementing and testing the solution and documenting the results. The results are reviewed at the status meeting for approximately 20 minutes before being closed. This yields a fully burdened per-discrepancy cost, not including equipment or materials, of:

$$\left[(2 \text{ people}) \times \left(\frac{3 \text{ hours}}{\text{person}} \right) + (2 \text{ meetings}) \times \left(\frac{8 \text{ people}}{\text{meeting}} \right) \times \left(\frac{0.333 \text{ hours}}{\text{person}} \right) + (5 \text{ people}) \times \left(\frac{8 \text{ hours}}{\text{person}} \right) + (2 \text{ people}) \times \left(\frac{3 \text{ hours}}{\text{person}} \right) \right] \times \left(\frac{\$75}{\text{hour}} \right) \cong \$4,300 \quad (8)$$

Thus, the estimated annual labor cost of handling discrepancies for the spacecraft in this study ranged from \$390K to \$1.16M. It is important to note that this estimate does not include the cost of equipment or materials, which can be considerable when the resolution of a discrepancy requires the purchase or replacement of a major component like a workstation, server, front-end processor, or ground station antenna motor.

Discussion

Sampling and Methodology

The true population of interest for a discrepancy data analysis is the set of all discrepancies occurring on all spacecraft launched since Sputnik. Obviously, it is not possible to characterize the entire population directly, so some sampling technique is required. This study concentrated on spacecraft that were either currently operational or recently decommissioned, as of May 2001.

The sample is not truly representative of the entire population, since it is weighted solely on operations within the last decade and does not take into account earlier missions. However, recently flown spacecraft are more relevant, and therefore of more interest, to existing and future satellite missions. Although older discrepancy data would provide a more comprehensive dataset, in many cases operator logs were not archived or are no longer available. Therefore, recent programs were the only ones used in this study.

The correlation analyses performed to test the second hypothesis indicate that correlations do exist between certain design elements and the types of problems experienced during operations. Such analyses require that the sample set be large enough and diverse enough to differentiate the effects of one design element from the effects of the others. For example, if “orbit characteristic” is the design element of interest in a particular analysis, it is desirable to have every possible value for “orbit characteristic” represented by several spacecraft in the sample. This would make it more likely to identify a trend, if one exists. However, the sample set used in this study did not fully explore all of the feasible combinations of values for all of the design elements. In some cases, like the “attitude control scheme” design element, the sample set was too uniform to represent the possible types of attitude control schemes. The results of several analyses were discarded due to this situation. The problem can be mitigated in the future by more aggressively selecting spacecraft to include in the sample set, specifically focusing on spacecraft which fully explore the design element trade space.

Observations on Data Collected

The process of merging data originally recorded using different techniques requires care and attention. The procedures for reporting problems vary from organization to organization, and the detail and content of reports can even vary from individual to individual using the same procedure within a single organization. In most cases, reviewing and categorizing each discrepancy report manually can overcome these variations, and was the approach used in this study.

Per Table 5, software glitches were identified as the root cause in an average of 48% of discrepancies reported for each spacecraft. Of all the discrepancies caused by software, 9% were attributed to spacecraft components and 91% were attributed to infrastructure components. It is relevant to note that most of the satellite programs included in this study used commercial off-the-shelf (COTS) software packages and/or hardware for data routing, telemetry processing, and command & control, or had transitioned from a legacy system to a COTS-based system at some point during the discrepancy reporting period.

Faulty equipment was found to be the root cause in an average of 9% of discrepancies reported for each spacecraft. A review of the corresponding discrepancy reports shows that equipment problems are most frequently attributed to computer hard drive failures, processor fan failures, damaged cables, faulty ground antenna amplifier equipment, and facility power/utility equipment.

Conclusions

This study intended to test the following hypotheses:

- **First hypothesis.** Most problems encountered by an operator do not involve the spacecraft at all, but are attributed to other elements of the space system.
- **Second hypothesis.** Correlations exist between aspects of a space system design and the nature of problems experienced by the operations staff over the long term.

An analysis of over 9,200 discrepancy reports from 11 on-orbit spacecraft supports the first hypothesis – 87% of the discrepancies collected were attributed to some component of the operational infrastructure. The remaining 13% involved one or more components on board the spacecraft. Software was the most frequently reported cause of discrepancies, found in 61% of all discrepancies documented.

The discrepancy reports also indicated that correlations do exist between certain design elements and the types of problems experienced during operations. The following correlations were found based on the data collected:

- **Ground System vs. Mission Type.** The percentage of discrepancies per spacecraft associated with the ground system tends to change given a particular mission type for the spacecraft.
- **Comm Relay vs. Ops Team.** The percentage of discrepancies per spacecraft associated with the communications relay tends to change from one organization to another.

Thus, the data collected supports the second hypothesis, but with the caveat that a sufficiently large and diverse sample set must be obtained to verify the results. It should be noted that causality cannot be determined from the statistical correlation analysis, but must be investigated on a case-by-case basis.

The results of this study can be extended by incorporating discrepancy data from additional spacecraft, particularly commercial programs. The methodology can also be applied on databases for individual satellite programs to gain insight into the nature and frequency of problems experienced by the operations staff. Ultimately, this can help supervisors identify strengths and areas for improvement in attempt to continuously improve the service provided to the user.

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